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SHORT CONTRIBUTIONS
to California Geology

SPECIAL REPORT 100

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AY MOBILITY,
ORTUGUESE BEND, CALIFORNIA *

PAUL F. KERR and ISABELLA M. DREW
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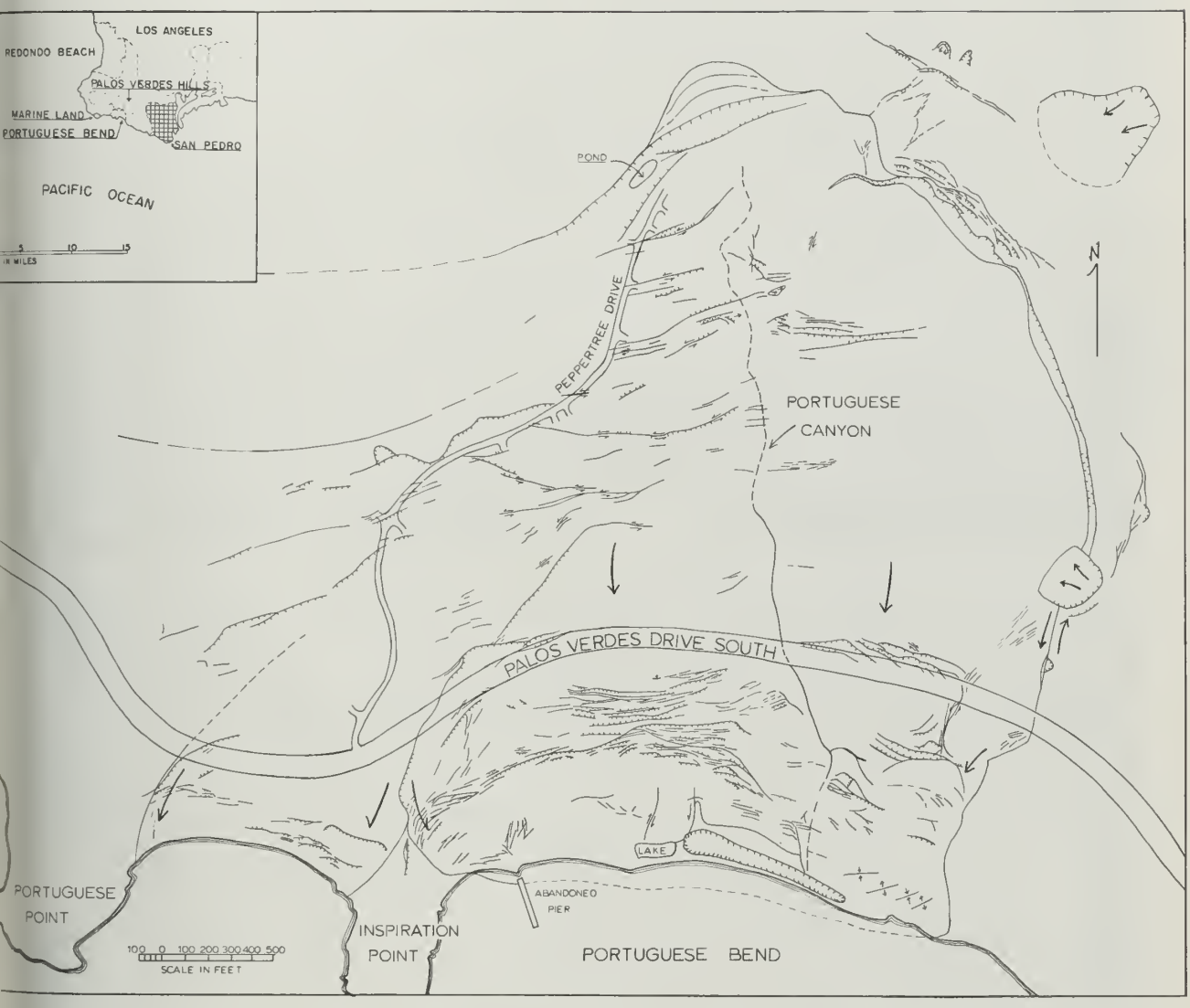


Figure 1. Location Map.

ABSTRACT

An unusual landslide occurs at Portuguese Bend on the rth slope of the Palos Verdes Hills west of San Pedro, lifornia. The slide has attracted wide interest because site is one of the choice residential areas of the south- st and 160 homes have been affected.

The slide movement began in a member of the Monterey ale that contains bentonite. Samples of bentonite from tuffaceous rocks are rich in Ca-montmorillonite. The y is stable when it is dry but swells and flows under pressure when it absorbs water. Laboratory studies show that the clay is thixotropic. Overlying stable shale beds are slowly rafted downslope on bentonite-lubricated slip planes. Movements of a small fraction of an inch per day have been measured, accumulating in a year to from 10 to 30 feet in places. Field observations indicate that the slide is constantly enlarging.

No completely successful method of controlling the landslide has been developed. However, adequate drainage, on the surface and along the slip plane below, would probably greatly reduce sliding.

anuscript submitted for publication July 1967.

Figure 2. The Slide in 1956 and 1965. In nine years, many houses were remaved from between the highway and the shore, as seen in aerial photographs of the area. Dashed lines an lawer phota indicate appraximate slide baundaries in 1965. *Phos Pacific Air Industries.*

INTRODUCTION

large, slowly moving landslide has long been gnized at Portuguese Bend (Woodring and others,) on the south slope of the Palos Verdes Hills, miles south of central Los Angeles, California 1). In 1956 the slide became considerably more e, following a surge in subdivision and building truction. By 1960 over a hundred homes were aged and most of them eventually had to be re- ed; property damage was estimated in the millions ollars (fig. 2).

the slide area appears now, a number of fea- indicative of slow but steady movement may be rved. The topography has undergone gradual but antial change. Palos Verdes Drive South, a four- highway across the slide area, has been repeatedly aged, and its uphill side had to be widened. Offsets ne pavement gradually develop at the east and slide boundaries. The landslide area between Verdes Drive South and the seashore is marked slide scars, cut by fissures (fig. 1), altered in elevations, and has shifted seaward (fig. 3). The pleasure pier at the Portuguese Bend Club stands isolated from the shore, club buildings have been removed, and the tennis courts are now tilted and fissured (fig. 4B). Power line poles and trees have moved. New water mains have been laid on the surface with special joints to provide adjustment for movement (fig. 5A). Secondary roads have been fissured, changed in grade, and even abruptly terminated in places. A concrete drainage ditch has been offset.

This investigation concerns mainly the clay involved in the underlying earthflow. It has been undertaken to provide additional data on the causes of sliding and to examine fundamental characteristics of the clay with a possible bearing on slide control. Discussion of the geological features is brief because more extended studies by Dr. Richard H. Jahns and George B. Cleveland, now nearing completion, will be published by the California Division of Mines and Geology.

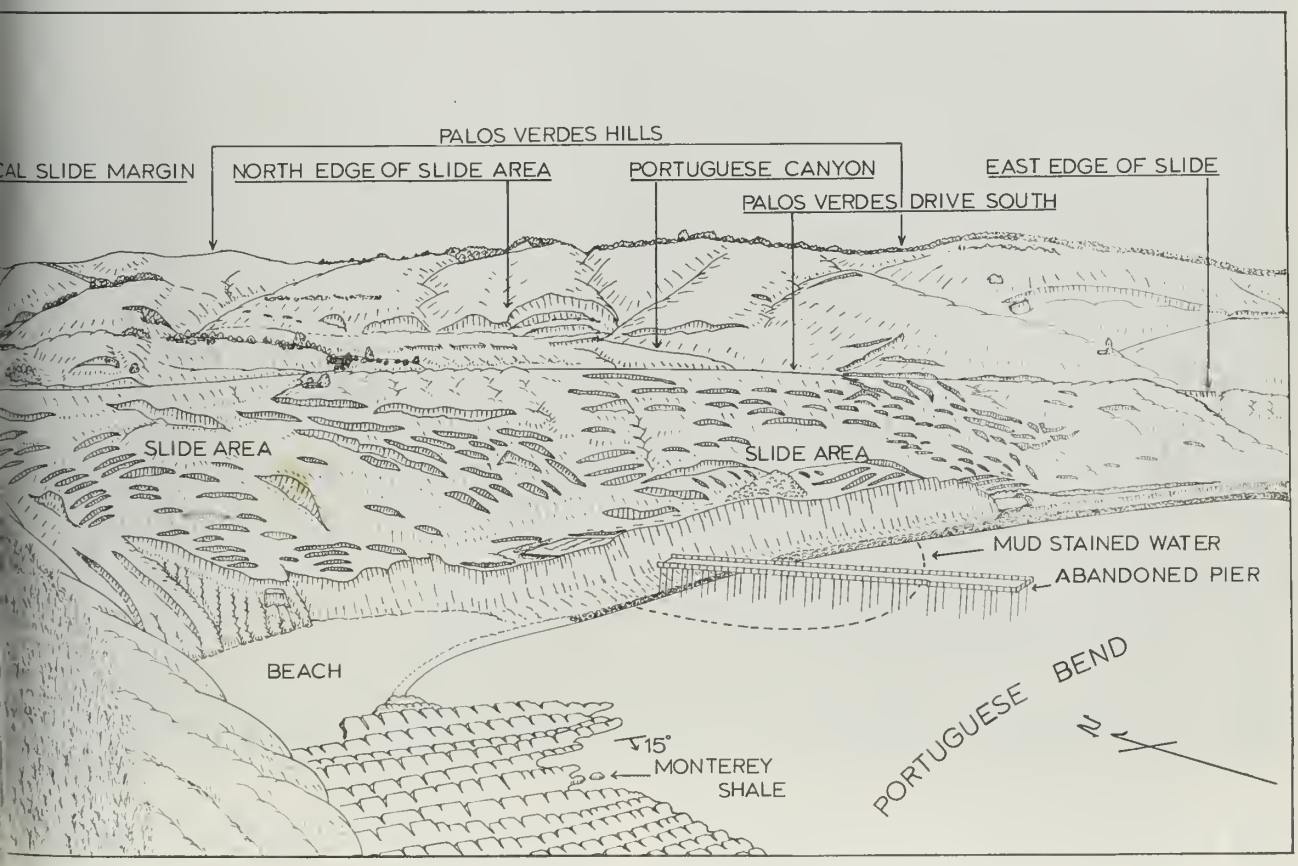


Figure 3. Sketch of Slide Topography as Observed in 1966.

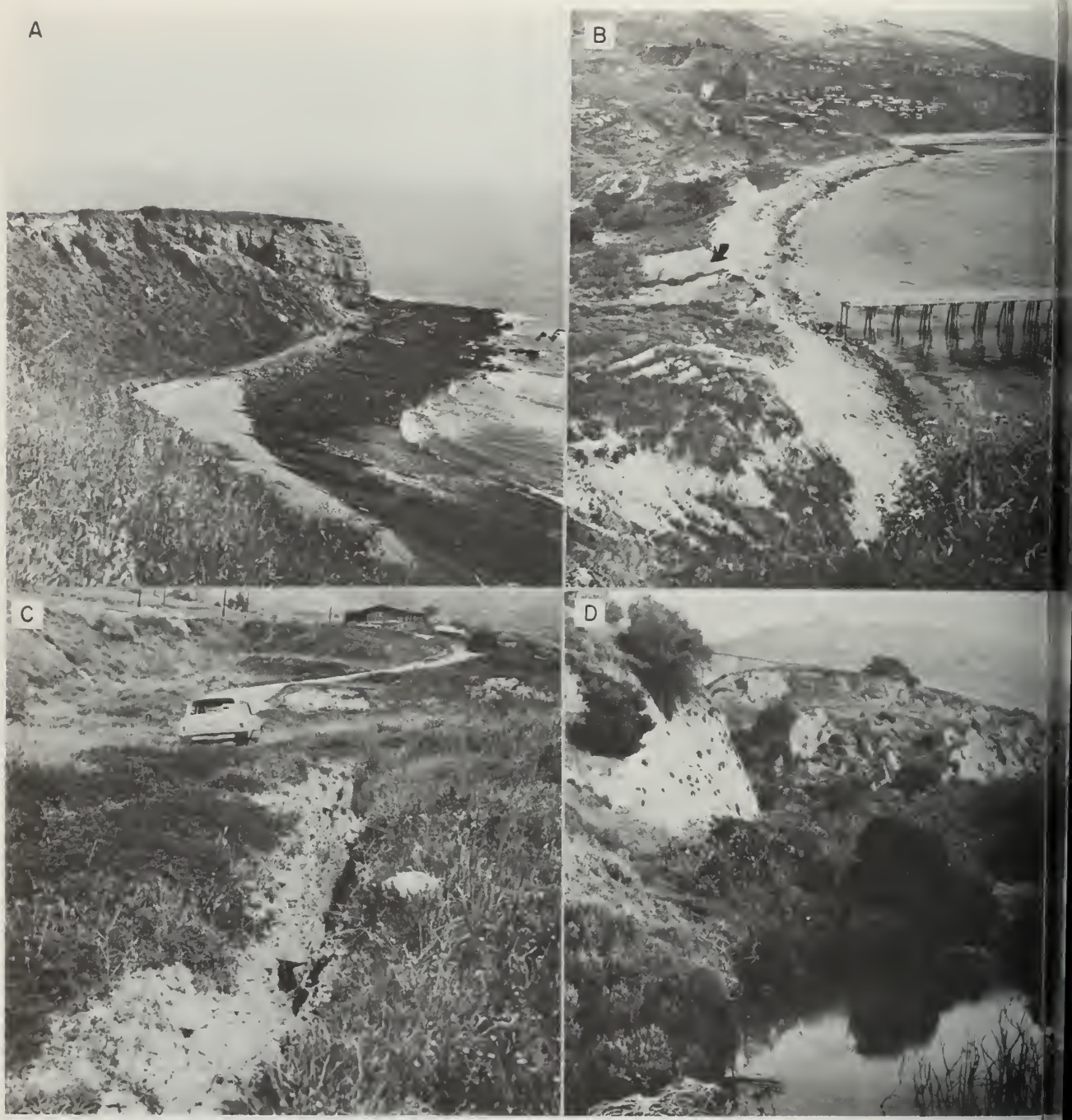


Figure 4. Stable and Mobile Areas. A. The cliff at Inspiration Point has remained stable. Resistant outcrops of Monterey Shale appear on the cliff and along the seashore. The view is to the east. B. Tilted tennis courts (arrow) and an abandoned pier appear in a view of the slide area south of Inspiration Point. C. One fissure in the slide area near Inspiration Point is about 20 feet deep. D. In A 1966, a pond had formed in a slump trench northwest of Pe Drive. Water from fault lines would be expected to increase the bility of bentonite along buried slip planes.

ACKNOWLEDGMENTS

This study has been made possible through the support of the U.S. Air Force Cambridge Research Laboratories. Captain James T. Neal has cooperated and furnished general guidance as contract monitor (AFCRL–67–0234). The writers thank Dennis A. Evans, formerly Head Engineering Geologist of Los Angeles County, Dr. Perry L. Ehlig, California State College, Los Angeles, and Stone Geological Asso for field data and several of the samples investi We thank Mrs. Joan Settle Thomas who carri many of the laboratory tests and aided in dr figures. We express our appreciation to Dr. Fe H. Jahns, Dean of the School of Mineral Sc Stanford University, and George B. Cleveland, f

rnia Division of Mines and Geology, who have d on extensive studies in the area and have offered suggestions from unpublished work.

GEOLOGICAL FEATURES

anticline, with a sinuous, but average N70°W, follows the crest of the Palos Verdes Hills of the Portuguese Bend landslide. The active rea extends up slope northward from the sea- about 4,000 feet and east-west about 6,000 feet.

As shown by Woodring and others (1946, pl. 1) on a geologic map and in the accompanying text, the slide occurs in the Altamira Shale Member of the Monterey Shale (Miocene).

The Monterey Shale, where free from bentonite and even where intruded by basalt, appears locally to form resistant masses not subject to slide action. This resistance is shown by Inspiration (fig. 4A) and Portuguese Points (fig. 1), which have long withstood extensive marine erosion.

5. Physiographic Features. A. Part af Palas Verdes Drive as relacated in February 1967. Service pipe with special jaint was laid an abandaned pavement. The view laaks sauthwest ast margin af the slide. B. Slide rotatian tilted a marine terrace inland. The view laoks west alang Palas Verdes Drive South at east margin af slide area. C. Slide actian depressed a carnatian nursery. The view is north. D. Narth of Palas Verdes Drive Sauth, a scarp barders the east margin af the slide area.

At least one large depression (fig. 4C) and several smaller ones appear to have been produced by block tilting with rotational movement. Sediments in sunken areas thus formed dip toward the head of the slide, as pointed out by Merriam (1960). More or less uninterrupted sedimentary strata in the shaly, tuffaceous and terrace material composing the slide indicate that, in places, blocks several hundred feet across must have moved almost intact (fig. 5B). Subsidence trenches occur near the heads of sliding units (fig. 4D).

Landslides at Portuguese Bend provide a complex of related lithologic, hydrologic, and structural features. The Altamira Shale Member of the middle to upper Miocene Monterey Shale, in which most sliding occurs, is at least 500 feet thick. This member has been invaded in places by basalt. Hard and essentially substantial cherty and silty shale strata make up the larger part of the section, but intercalated are several thin tuff beds, which are in part bentonite. Above these is the Miraleste Tuff bed. Although absent in some places, it is ordinarily two to four feet thick and ranges up to eight feet (Woodring and others, 1946, p. 19). The Portuguese Tuff bed near the bottom of the Altamira Member is a light buff-colored tuff 60 feet thick (Woodring and others, 1946, p. 18) that is partly bentonitic (Woodring and others, 1946, pp. 21–22). Slide action was long ago attributed to movement along a gliding plane formed by water-soaked bentonitic tuff. A schematic cross section of the Portuguese Bend landslide is shown in figure 6. It is based on stratigraphic data by Woodring and others (1946, pp. 20–21), their geologic map (1946, pl. 1), subsurface contours of the slip plane by Stone Geological Associates, and geological observations made in connection with this study.

The dip of the slip plane is south, aside from a concave depression beneath the sea-cliff, where it extends below sea level and emerges off shore. Mud apparently extruded from the Portuguese Tuff bed on the ocean's floor stains the water near the abandoned pleasure pier (fig. 3).

EARTH MOVEMENTS

Beginning in 1956, approximately one-fourth of t previously known landslide area became notice more active. Earthflow at the rate of 0.03 to 0.1 per day down a mean slope of 6.5° has continued s that time. In a residential area the cumulative ef of such slide action may be highly damaging, b is not immediately devastating.

The cause of the slide action is of interest. In a s area of such slow movement, long and irregul active as observed for several years, initiation of s action by earthquakes seems unlikely, althoughn earthquake study of the area has been made. At n rate, it is evident that no rapid clay flowage dire related to an earthquake, as occurred at Anchor Alaska on March 27, 1964, has taken place (Kerr n Drew, 1965). Local blasting in nearby highway c struction would appear equally doubtful as a ca In fact, movement amounting to about 10 inches c curred on Palos Verdes Drive South between Febru and July, 1967, when no highway was under c struction. Merriam (1960) has suggested that w erosion of the cliffs in the lower end of a seav plunging structural trough may have initiated the s slides. However, in such a slowly moving slide, w conditions likely to cause slide action exist, mover may be spontaneous, and the mineralogical nature physical conditions of slide material probably co tute the most important factors. Studies of movem in quick clay slides (Liebling and Kerr, 1965) sup this conclusion.

Merriam (1960) feels that a favorable combina of geologic conditions localized and initiated movement. Although rainfall in the winter prece sliding was only moderately above average, Mer thinks that the manner in which it came increase effectiveness: "Following several dry years du which desiccation developed deep cracks, near inches of rain fell in less than a week. During hi week Portuguese Canyon, which passes through

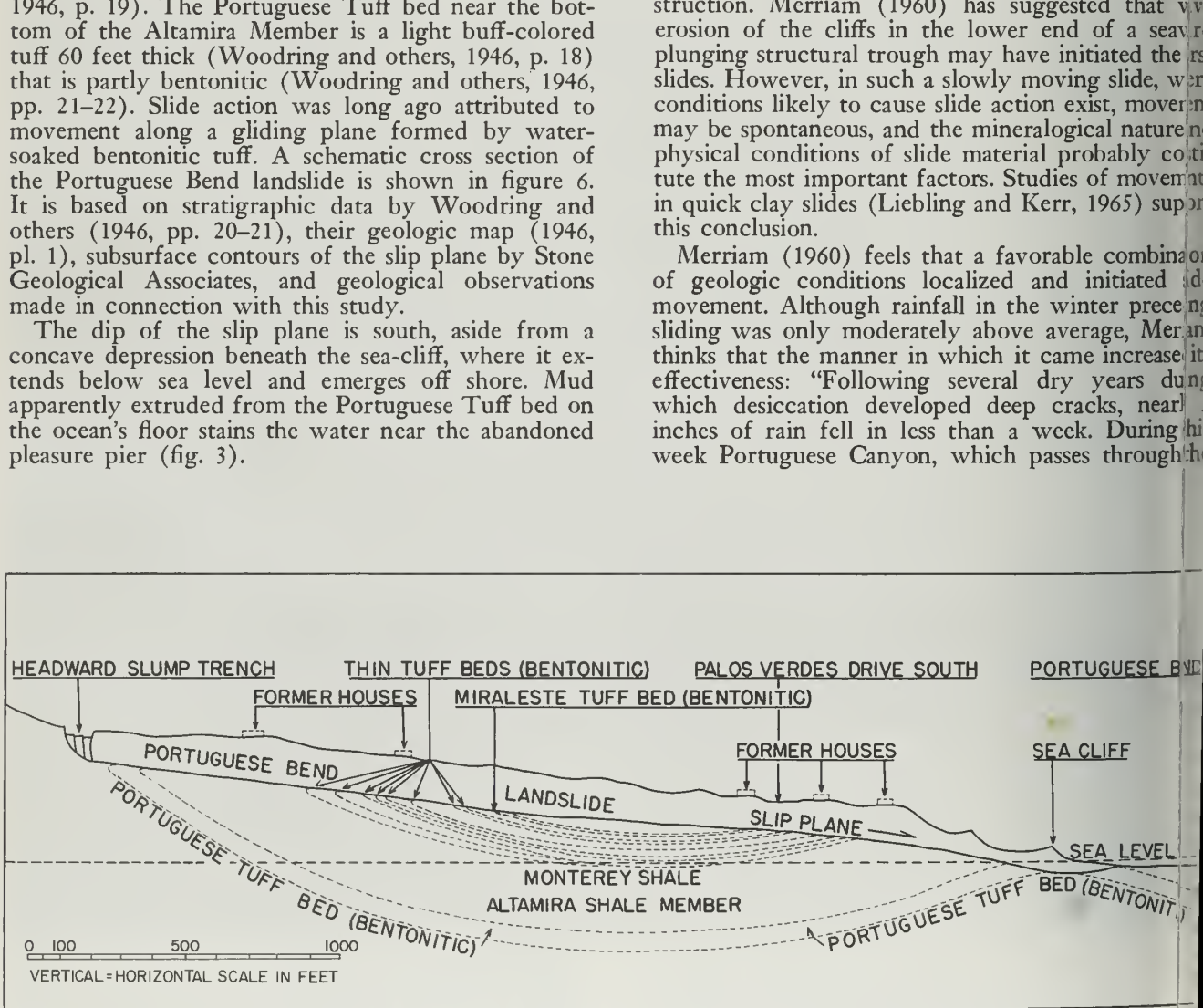


Figure 6. Approximate Structural Interpretation. Schematic cross section shows features of the slide.

:r of the active slide, discharged no water to the Open cracks in its shattered clayey bed could have tted much water" (Merriam, 1960, p. 150). In ion, Merriam estimates that at least 32,000 gallons lay entered the active landslide through cesspools. further possible that organic matter from these ools may have contributed a peptizing effect on lay strata. As van Olphen (1963, p. 109) points ". . . the addition of a few tenths of one per cent ese chemicals is often sufficient to turn a stiff con- ated clay suspension into a rather free-flowing d." A small amount of peptizer greatly decreases ield stress of a pure clay gel. White and Kyriazis 8, p. 16–19) have shown that waste effluents ma- ly and adversely alter the Atterberg limits of morillonite.

esent movement south of Palos Verdes Drive n consists of slow earth movement in which ed debris and bentonite undergo plastic flow. h of the drive, larger blocks may move fairly t (fig. 5B), but are shifted relative to one another n places exhibit marginal fissures. At the head of lide, block rotation may be observed (fig. 4D). A c variation in slide movement can be correlated precipitation, slippage following rainfall by sev- nonths (Merriam, 1960).

rth movements along the east side of the landslide it a pattern of considerable interest. A 1946 pho- ph of this area (Woodring and others, 1946, pl. ooking west from the east border of the slide, s Pleistocene marine terraces sloping moderately ward toward the Pacific Ocean. Recent observa- , although only partly supported by survey data, of such magnitude as to clearly show major ges in slide topography since 1946. The sea cliff (fig. 5A) has undergone substantial uplift and ap- tly some migration seaward. As shown by scat- patches of broken pavement where the highway to be, Palos Verdes Drive South is now at least eet north of its position in 1956 (fig. 5A). The ce area north of Palos Verdes Drive South now s northward away from the Pacific Ocean (fig. nd forms an undrained basin tens of feet deep.

SAMPLES EXAMINED

terial examined from the Portuguese Bend slide

Sample A. Highly expansive yellowish-gray entonite from a cut on the south side of Palos erdes Drive South, about 100 feet east of the ctive slide boundary.

Sample B. Greenish bentonite from a slide lane taken in a boring made in the summer of 959 near the head of the slide area. Sample was ken after the boring was offset by slide move- ent.

Sample 1. Gray to tan brecciated bentonitic ay from a road cut along Palos Verdes Drive uth about 75 feet east of the edge of the slide.

Sample 2. Mottled bentonite mass mixed with oken strata from the slide toe collected from the base of the sea cliff near the former Portuguese Bend Club pier.

Sample 3. Gray to tan bentonite from a cut along Peppertree Drive in the northwest part of the active slide.

Sample 4. Lignitic shale collected near the slide area.

Sample 5. Diatomite from crest of the Palos Verdes Hills collected northwest of the slide area.

Samples A and B were kindly supplied by Dr. Perry L. Ehlig, California State College, Los Angeles.

Mineral Content

Samples A, B, 1, 2, and 3 are all bentonitic. The clays are highly expansive; their dry strength is great, but they absorb water readily, expanding to approximately twice their dry bulk and finally, upon continued addition of water, form a sticky to soupy slurry. These five samples give sharply defined x-ray diffractometer patterns for montmorillonite (fig. 7). X-ray data, simple ion-exchange tests, and a liquid limit considerably below the value for Na-montmorillonite indicate that the clay mineral is relatively well crystalized Ca-montmorillonite, with some quartz in the coarser fractions.

Montmorillonite in bentonite clay has been recognized previously in similar Miocene shale at Ventura, California (Kerr, 1931). On the basis of chemical analysis and x-ray diffraction data, it would be classed as calcium montmorillonite.

Thin sections were made from Sample 2. Embedded in the extremely fine-grained matrix of bentonite are rounded particles averaging 0.5 to 1.0 mm. in diameter and composed of aggregates of clay flakes. In studies elsewhere, such particles have been interpreted as remnants of altered tuff (Schultz, 1963, p. C31). In the samples examined, alteration has apparently destroyed all traces of shards.

Sample 4, a lignitic shale, with 4.36 per cent organic matter, is typical of the stable cherty and silty shales found in the slide area. Quartz and feldspar fragments form the bulk of this material. The mass disaggregates to some extent in water but does not swell or become plastic. X-ray diffractometer studies indicate that a small amount of illite-montmorillonite interlayered clay is present. Interlaying was not observed in the bentonite samples.

Sample 5, diatomite, shows typical diatom structures upon microscopic examination. The X-ray diffractometer patterns indicate that this bulky material has rather poor crystallinity. The diatomite gives a negative test for carbonate and is not disaggregated in a 5% water solution of the dispersing agent sodium metaphosphate.

Particle Size Measurements

The hydrometer method (A. S. T. M. D-22, 1965) was used to determine the particle size range of the bentonites from Portuguese Bend. These clays are

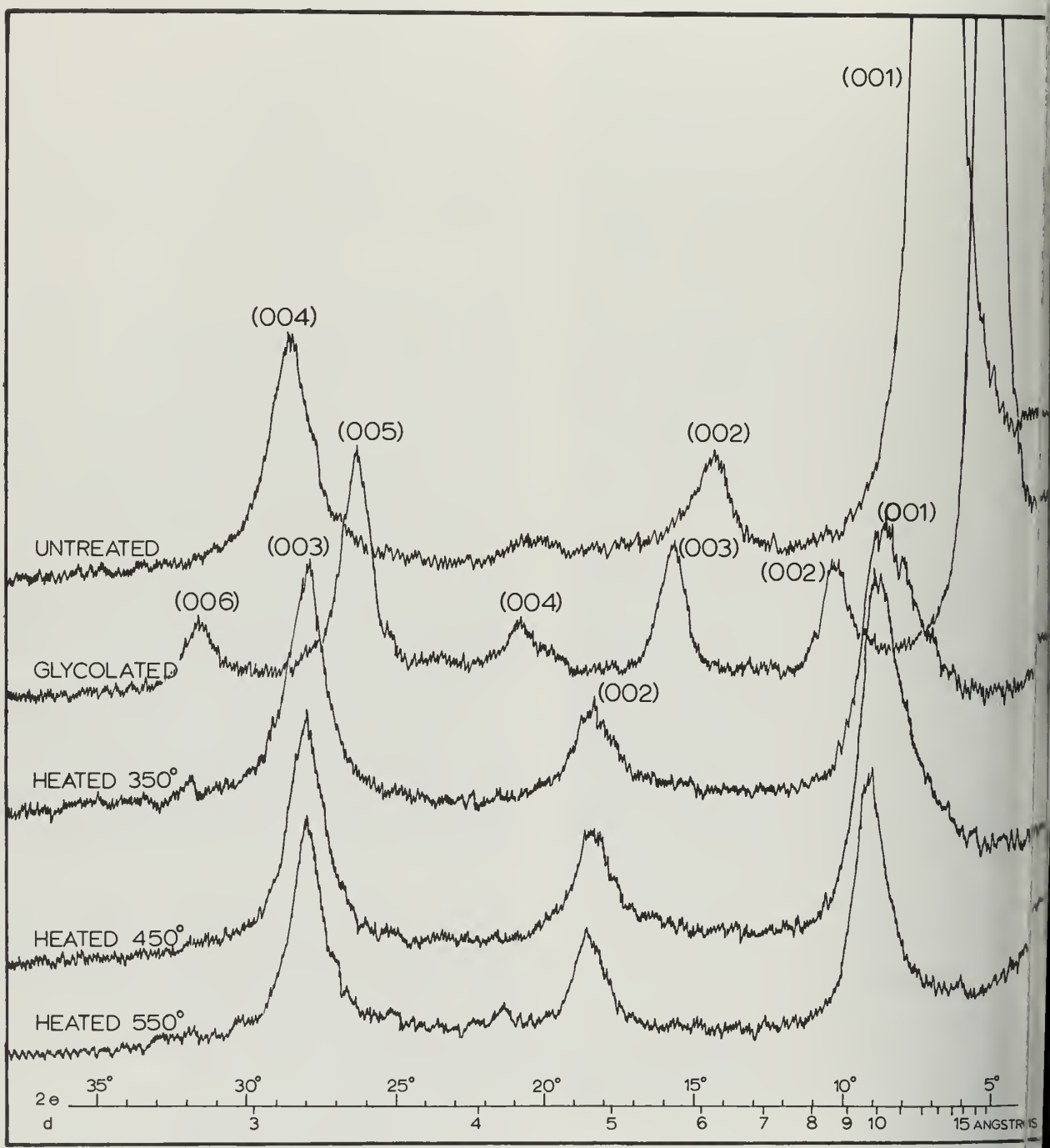


Figure 7. Patterns of Montmorillonite. X-roy diffroctometer patterns of montmorillonite oppeor in <2μ froction of Sample 2. The (001) reflection expands 14 Å to 17 Å on glycolation. The structure collopses reversibly to 10 Å ot temperotures os low os 350° C. irreversible collopse is not encountered until 550° C., ... montmorillonite onhydride or illitic structure is formed.

characterized by an unusually high colloidal content. They are gap-graded with some silt-sized particles present in all samples. Because only traces of quartz or other mineral fragments are present, as shown by x-ray diffractometer and microscopic investigation, these coarser particles are thought to be tuff p... Water-saturated samples of the bentonite are g... the grains apparently consisting of aggregates ... tially altered volcanic material. Histograms (g... illustrate particle size distribution. Samples 1, 2...

from active slide areas and contain 60 to 70 per clay-sized (<2μ) material. Sample A, from d cut to the east of the active slide area, bly from the Portuguese Tuff Bed, contains con-bly less fine clay (47 per cent). The particle istribution curve shows this sample to vary from hers in being well-graded rather than gap-graded).

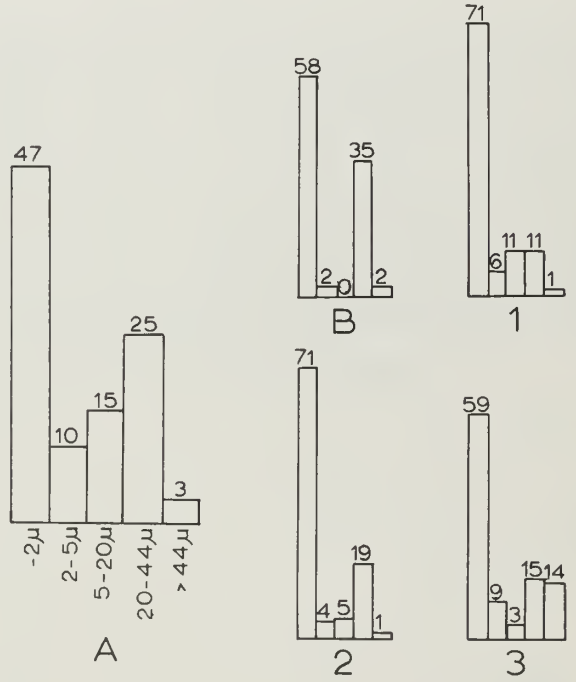
Physical Properties of Clays

ples collected by Kerr during August, 1964, found to have a natural moisture content of 62 ent. However, moisture contents determined in oratory are always lower than the natural water t of the material in place. Liquid limits for the itic samples ranged between 90 and 110, plastic

Viscosity and Flow Characteristics

One of the most remarkable features of bentonite from Palos Verdes is the ease and rapidity with which colloidal gels are formed. Gel formation led to considerable difficulty in determination of particle size ranges by the ASTM hydrometer method in certain samples. Only 50 grams of bentonite dispersed in 1,000 ml. of 0.5 per cent sodium of metaphosphate solution were found to form a gel firm enough to support the weight (70 grams) of the ASTM soil hydrometer, regardless of the depth at which it was placed.

Quantitative measurements were made of the flow properties of the <2μ fraction of the clay by means of the Brookfield Model RVT Viscometer. The



e 8. Histogroms of Particle Size Distribution. Samples are es from the Palos Verdes Hills. Sample A, fram outside the slide ontoins the smallest amount of clay-sized material.

between 60 and 70. Thus, even during the drier r season, the natural moisture of these clays lies the range of plastic behavior.

those unfamiliar with the nomenclature conven-sed in soil studies, it should be noted that per oisture content is always expressed as the ratio weight of water to the weight of dry clay. For e, if 10 g. water are added to 10 g. clay, the e content of the resulting plastic mass is 100 it.

ily sedimented bentonite was found to have a itation bulk density of only 0.2g/ml. in distilled Thus it may be concluded that unconsolidated iese Bend clay can hold four to five times its of water without becoming fluid. This clay y plastic, however, and the shear strength is

yellowish-tan colloidal suspension investigated consisted of 23 parts of water to 1 part of dry clay. The actual viscosity of the system, measured on the Brookfield Helipath Stand with Spindle T-A at 1 RPM, was found to be 128 poises. Clays from Anchorage, Alaska; Oslo, Norway, and certain other localities in California, investigated by Drew using the same Viscometer, showed no measurable viscosity at such high water contents.

The Palos Verdes bentonite is highly thixotropic. When the viscosity of the <2μ clay fraction is plotted against the time elapsed, the viscosity decreases as the system is subjected to constant shearing (fig. 10). This is typical of thixotropic gels. The colloidal structure is almost completely destroyed in the bentonite after about 10 minutes at a rate of shear of 0.5 RPM.

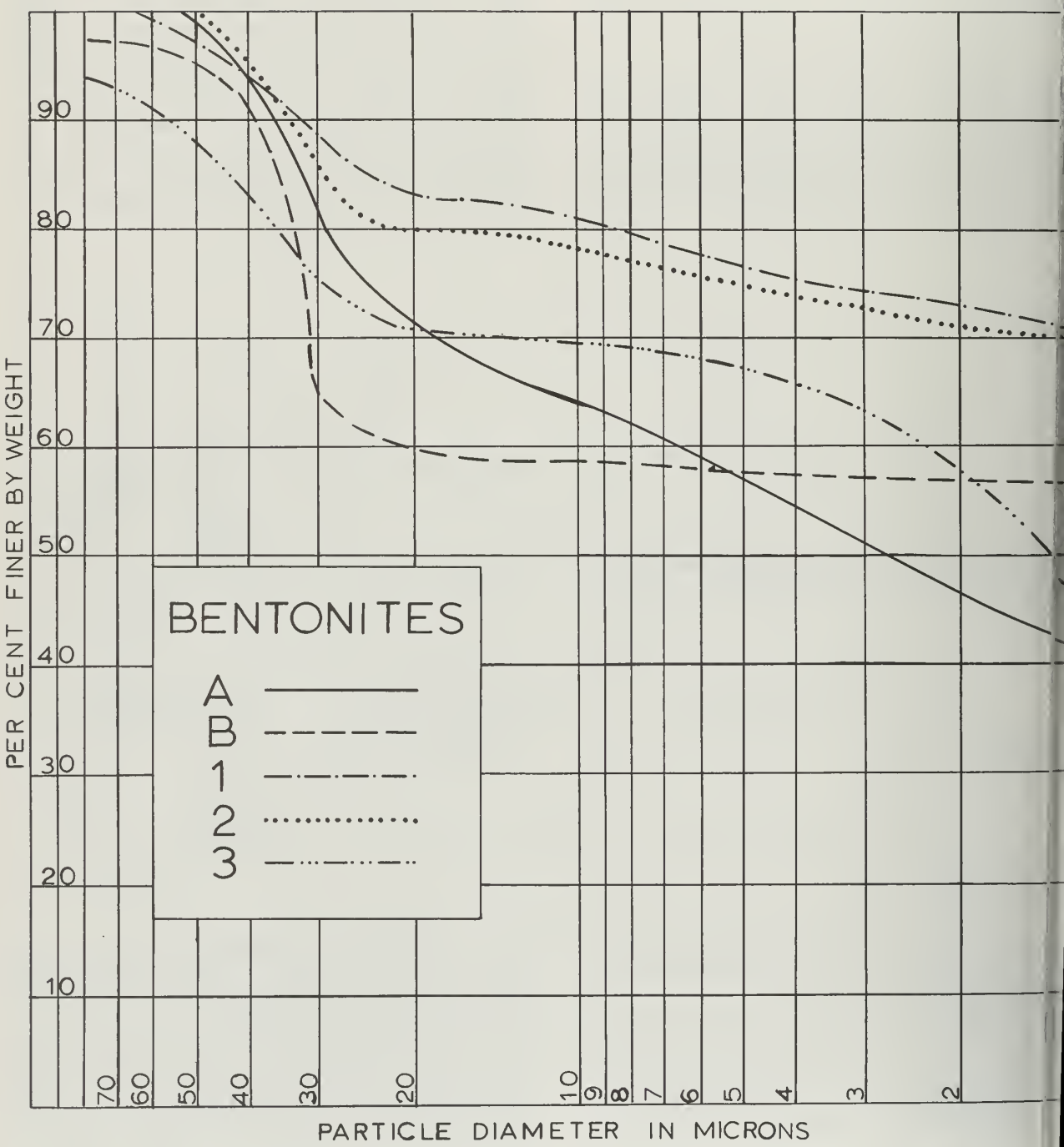


Figure 9. Curves of Particle Size Distribution. Most of the samples are gap-graded, consisting chiefly of colloidal material and t
a few per cent coarser.

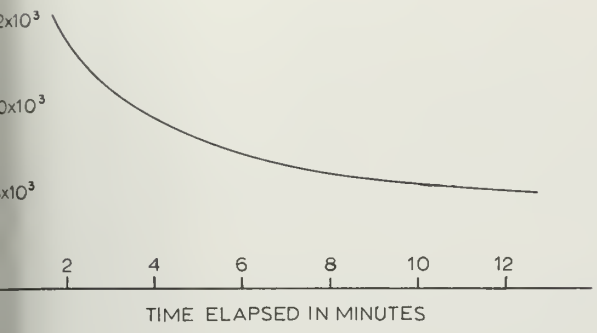


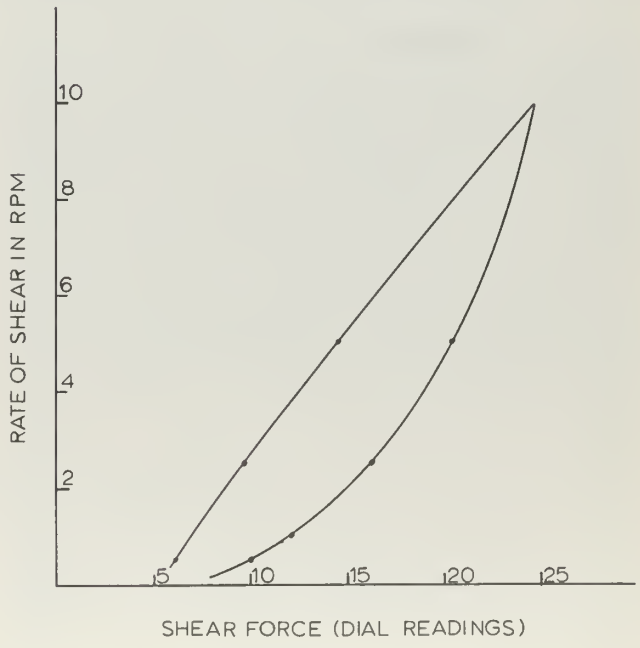
Figure 10. Decrease in Viscosity Under Shearing. Viscosity decreases with time as the thixotropic gel breaks down.

When the rate of shear was increased from 0.5 to RPM and then decreased again, a hysteresis loop . 11) was obtained, illustrating the fact that, in otropic clays, the shear force, and viscosity, at any n rate of shear is dependent on the amount of pre- s shear the system has undergone. Shearing causes kdown of the particle links in the skeleton struc- of the more or less flocculated clay-water system, reducing the viscosity of sheared clays.

When the thoroughly stirred clay-water system was wed to stand for increasing periods of time, the inal viscosity was regained, indicating that Brown- movement of particles permits the re-establishment of the sheared links in the colloidal structure. Thixotropic regain was found to be rapid for the first 15 minutes, during which time approximately half of the original viscosity was regained. Approximately 90 minutes is required for complete regain of the original viscosity.

The clay was found to be rheopectic, that is, the rate of stiffening increases when the beaker containing the suspension is tapped lightly. Rheopexy is a consequence of the increased particle collision frequency in a gently agitated system. Under mild agitation, Palos Verdes clay regained its viscosity in approximately 35 minutes.

ure 11. Hysteresis Loop. This hysteresis loop was obtained for Verdes Hills clay.



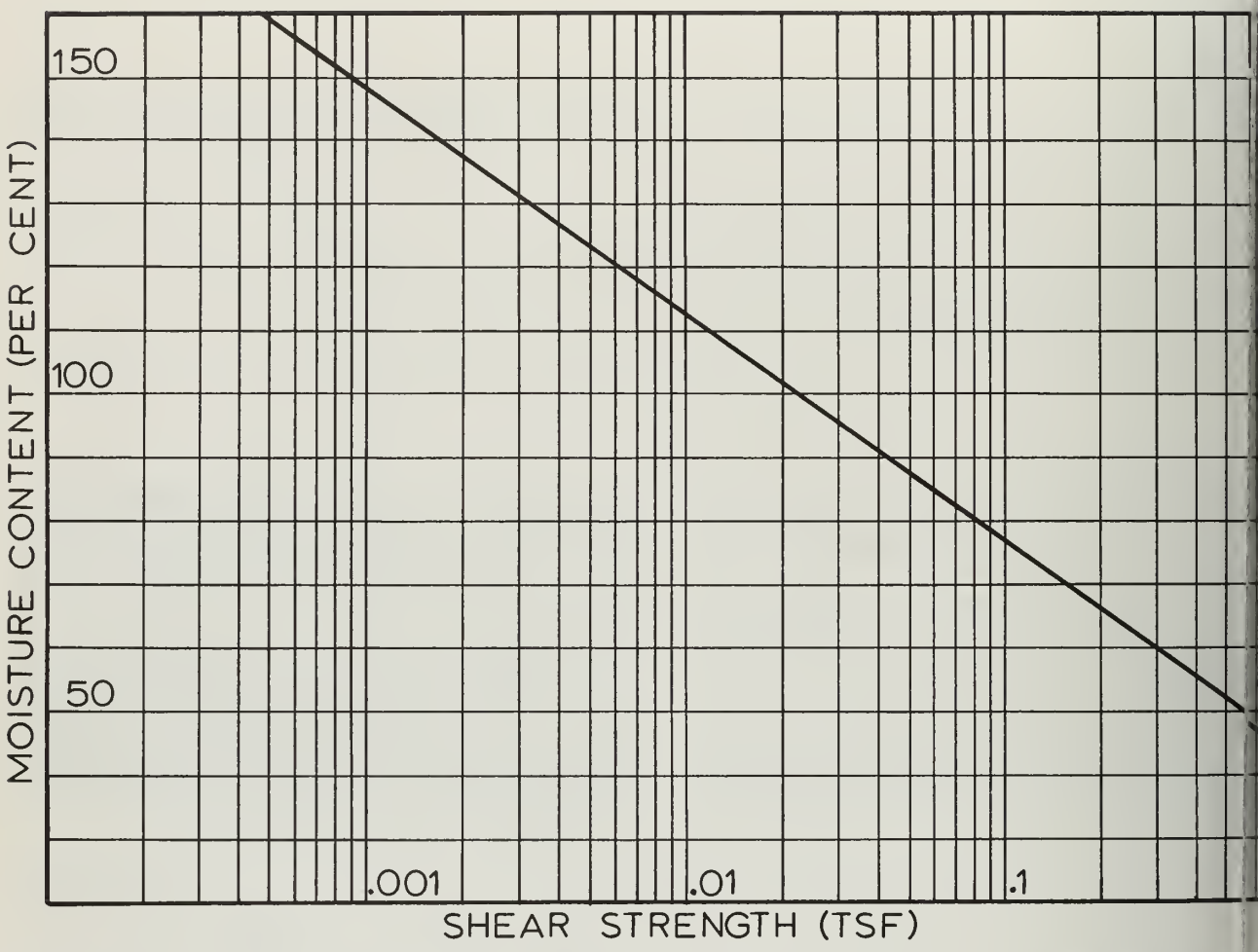


Figure 12. Water Content and Shear Strength. An increase in moisture means a decrease in shear strength, as measured with Swedi Shear strength is in tons per square foot (TSF).

Influence of Water Content

Water content has a great effect on the properties of the bentonite of the Palos Verdes Hills. As can be seen from figure 12, doubling the moisture content decreases the unconfined shear strength by more than 10 times. At the moisture content measured for the Palos Verdes clay, shear strengths would be on the order of only ¼ ton per square foot.

An experiment was devised to study the influence of water content and overburden pressure on the stability of the clay strata at Portuguese Bend. A layer of bentonite ½-inch thick was spread between two rigid boards and the system adjusted to a constant slope of 1:10. The water content of the clay stratum was changed by the addition of increments of distilled water. The exact water content was measured after each test by oven drying and weighing samples of the clay. Loading of the upper board was also varied. Clay flowage was measured by timing the relative movement of vertical marks on the boards. The results of this experiment are illustrated in figure 13. At moisture contents greater than 120 per cent, the clay exhibited a slow plastic flow without loading. Loads s e would cover a range of about 0 to 150 feet, t mated thickness of material above the slip p n Portuguese Bend. As the load was increased, th w content at which the clay would show mo n within a 24-hour period decreased. In this way, g of stability and instability could be identifi . though an artificial model, this experiment is suggestive in considering movement of rock m s moist clay under the field conditions at Por g Bend.

Influence of Additives

Experiments were conducted in order to inv ti the influence of lime on the physical prope ie bentonite of the Monterey Shale, Palos Verde Table 1 summarizes the results.

It appears that lime may be effective in inc the shear strength. Although the actual values a e the addition of only 2.5 per cent lime more tha r the relative shear strength, even at high moistu tents. Lime also increases the liquid limit a d plastic limit but decreases the plasticity inde

easing the amount of water necessary to produce tic flow in the clay.

he effect of other calcium and aluminum salts on s Verdes clay was measured. Air-dried clay was ed with varying proportions of distilled water, sat- ed gypsum solution (about a 0.2 percent solution $CaSO_4 \cdot 2H_2O$), and about a 5 per cent solution of $(SO_4)_3 \cdot 17H_2O$. These two salts do not affect the id limit of the clay, but increase the plastic limit 20 and 30 per cent, respectively. This may be ad- ageous because apparently it would require a ter water content before the clay would exhibit tic behavior.

xperiments were conducted to determine the effect alcium and aluminum sulfate solutions on the shear ngth. Shear strength was measured with the Swed- Cone on clay blocks prepared with different con- rations of the solutions. It was found that at any n moisture content the shear strength is decreased he addition of calcium and aluminum sulfates in concentrations tested. Aluminum sulfate decreased strength to a greater degree, probably because of much greater solubility. The presence of sulfates arently also increases the effect of moisture content shear strength. That is, shear strength decreases e rapidly with increasing moisture content when ate salts are present than when they are absent.

urther experiments were carried out using "Ben- ," * which reacts rapidly with the clay and yields hesive granular product. The "Bengum" appears orm a coating for the Palos Verdes clay that may ent further water absorption and swelling. The dity of the action between the "Bengum" slurry the water already present, however, prevents etration of the stabilizing agent into the clay mass. erefore, only the surface of the clay is affected.

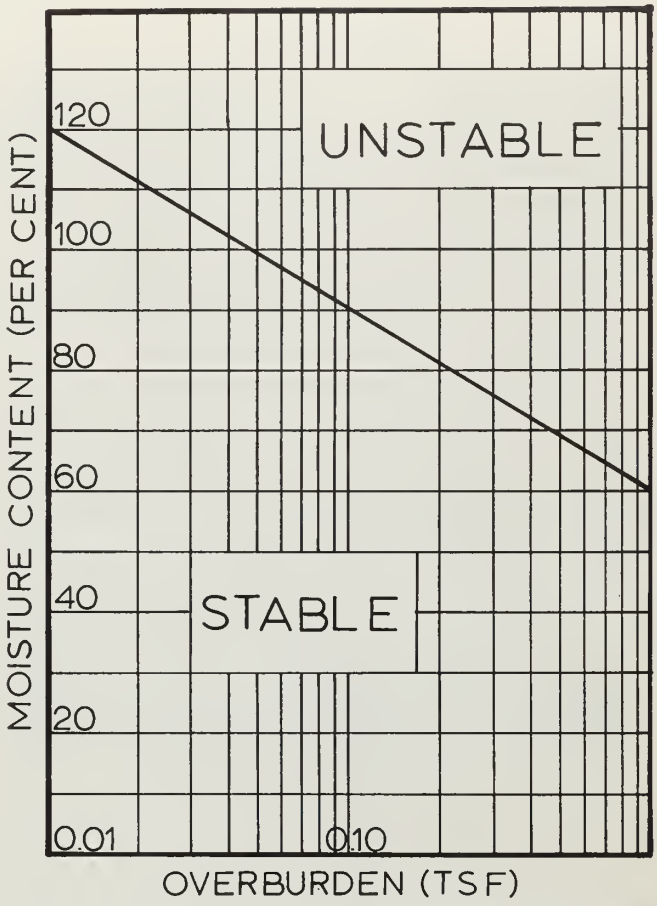


Figure 13. Water Cantent, Overburden Pressure and Stability. The greater the averburden pressure, the lower the water content needed ta praduce mavement in Palas Verdes Hills bentanite.

METHODS OF SLIDE CONTROL AND PREVENTION

everal control methods have been tried and sug- ed at Palos Verdes. In 1957, the installation of 35 sons 4 feet in diameter and 20 feet long made of forced concrete failed to hold the sliding. Some of caissons failed through tilting, others were sheared crushed, and slide debris moved around the re- ning few in plastic flow. A program of fill and tment at the toe reached the planning stage and e preliminary rock fill was placed, but the pro- n was subsequently abandoned. Such a program ht be effective in maintaining equilibrium by pre- ing erosion at the toe but probably would not be cient in itself to halt the slide.

Culverts and fill have been used in an attempt to prevent the entry of surface water into the clay strata. Unfortunately, slide movement has caused old filled cracks to reopen and new cracks to form.

The single most effective means of preventing slid- ing would appear to be the elimination of excessive water in the clay. At least it would appear feasible to drain water as accumulated in the slump trench at the head of Peppertree Drive (fig. 4D). A program of drainage with upward sloping perforated pipe in the slide area, coupled with the diversion of water from the head of the slide, would be helpful. This might be supplemented by the introduction of additives, such as lime, which should increase the shear strength of the clay. However any attempt at slide drainage and clay stabilization should be preceded by a program of field research in a selected experimental area.

* roduct of the Halliburton Company, Duncan, Oklahoma.

Table 1. Effect af Lime an Atterberg Limits and Shear Strength

	LL	PL	PI	Shear Strength
Clay in distilled water	110	71	39	0.02 TSF (at 113 per cent H_2O)
Clay in 2.5 per cent lime	123	102	21	0.07 TSF (at 114 per cent H_2O)

CONCLUSIONS

Ca-Montmorillonite, in $<2\mu$ particles, with highly adsorptive properties, a low shear strength when wet, and a notably thixotropic behavior, is a recognizable constituent of tuffaceous beds of the Monterey Shale at Portuguese Bend. This material apparently provides lubricated surfaces along which more substantial overlying siliceous shale moves gradually oceanward.

Mobile clay consisting essentially of montmorillonite is believed to be extruded from slip planes or a zone of slippage that emerges beneath the ocean.

No successful program of slide control has yet been demonstrated. It would appear, however, that any program to be effective should first establish underground drainage of the slide area. This is indicated by the effect of moisture on the nature of the montmorillonitic clay and on its wide distribution.

Laboratory data point to a noteworthy increase in the shear strength of the clay when the water content falls. Such data also suggest a further increase in shear strength through the use of lime. However, load data indicate that, along the buried slip zone, the water content must be considerably lower than at the surface to yield a corresponding shear strength.

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E CHEMICAL 'FINGERPRINTING' ACID VOLCANIC ROCKS*

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ABSTRACT

uaternary rhyolites and dacites (obsidian and pumice) California, southern Oregon and western Nevada been analyzed (by x-ray fluorescence) for the ele- s Ti, Mn, Co, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Ba, Ce, Pr, Nd, Pb and Th. The concentrations of some ele- s (e. g., Ba, Sr, Zr) vary considerably with the source ities of the samples. These differences may be used to acterize or "fingerprint," with one exception, the acid sive rocks from each eruptive center. These data indi- that the source material and/or physico-chemical tic process of these acid volcanic rocks has varied center to center. However, the ratio K/Rb varies larly with increase in K and has an average value of for the rhyolites. Exploratory data have been used ggest, or eliminate, possible eruptive sources for ash sits (Pearlette) and also sources of obsidian used as material for California Indian artifacts.

INTRODUCTION

ngealed natural acid liquid, or obsidian, has al- s held a special place in petrogeny's theory (Bowen,); certainly it holds no less a place in the history an. Obsidian has been widely used in the past as w material for the manufacture of weapons and , but, as its natural occurrence is confined to nic areas, there is generally only a limited number urces of raw material in any one region (unlike which is a widespread European artifact source rial). If the source of obsidian used for artifact ifacture throughout a large area may be identified, trading links for its distribution may become nt; such a study of obsidian both as raw material is artifacts in the Near East has been made by rew and others (1966) using the optical spectro- as an analytical tool to characterize the obsidians. ochemically, it may not be surprising that obsid- found over a broad area—for example, in and d the Mediterranean region (Cann and Renfrew, —may be characterized by their assemblage of elements, for, in this region, there are numerous ic centers, many of which have lava of distinc- f not unique, composition. However, even in the more restricted area of Scottish Tertiary volcanism, it is possible to "fingerprint" pitchstone (hydrated obsidian) found in the island of Arran, and so distinguish it from pitchstone from the not so distant isle of Eigg (Carmichael, 1962).

Any analytical technique used to distinguish obsidians of various localities will, ideally, have to be non-destructive, or so sensitive that only a small sample is required, and it will also have to be reasonably rapid to be of use in the identification of large numbers of artifact samples. Moreover, it is the trace element assemblage rather than the major elements that may prove to be diagnostic, as the major element concentrations of fresh unaltered obsidians (neglecting the rarer peralkaline varieties) commonly show only limited variation, as may be seen in the tight clustering of acid lava analyses when recalculated into their salic normative constituents (Tuttle and Bowen, 1958, p. 78). An example of this limited variation in composition is shown in figure 1, where many of the analyses of obsidian and pumice samples (Carmichael, 1967) used for trace analysis in this paper have been plotted; they characteristically shown only limited scatter.

The purpose of this paper is to show that not only obsidian suitable for artifact manufacture, but also all varieties of acid lava (e.g., pumice, porphyritic obsidian and dacite) found in the Quaternary volcanic centers of California, southern Oregon and western Nevada may be "fingerprinted" by using a rapid, often non-destructive, x-ray fluorescence analytical technique. Several implications and applications of this "fingerprinting" are considered: firstly, each sampled Quaternary volcanic center has produced acid magma as pumice or obsidian of similar gross composition but unique in fine composition; secondly, it may be possible to identify the eruptive source for pumice found in widely distributed sedimentary sequences; and lastly, it is often possible to identify the geographical source of obsidian used to make artifacts, and therefore to determine possible trading links.

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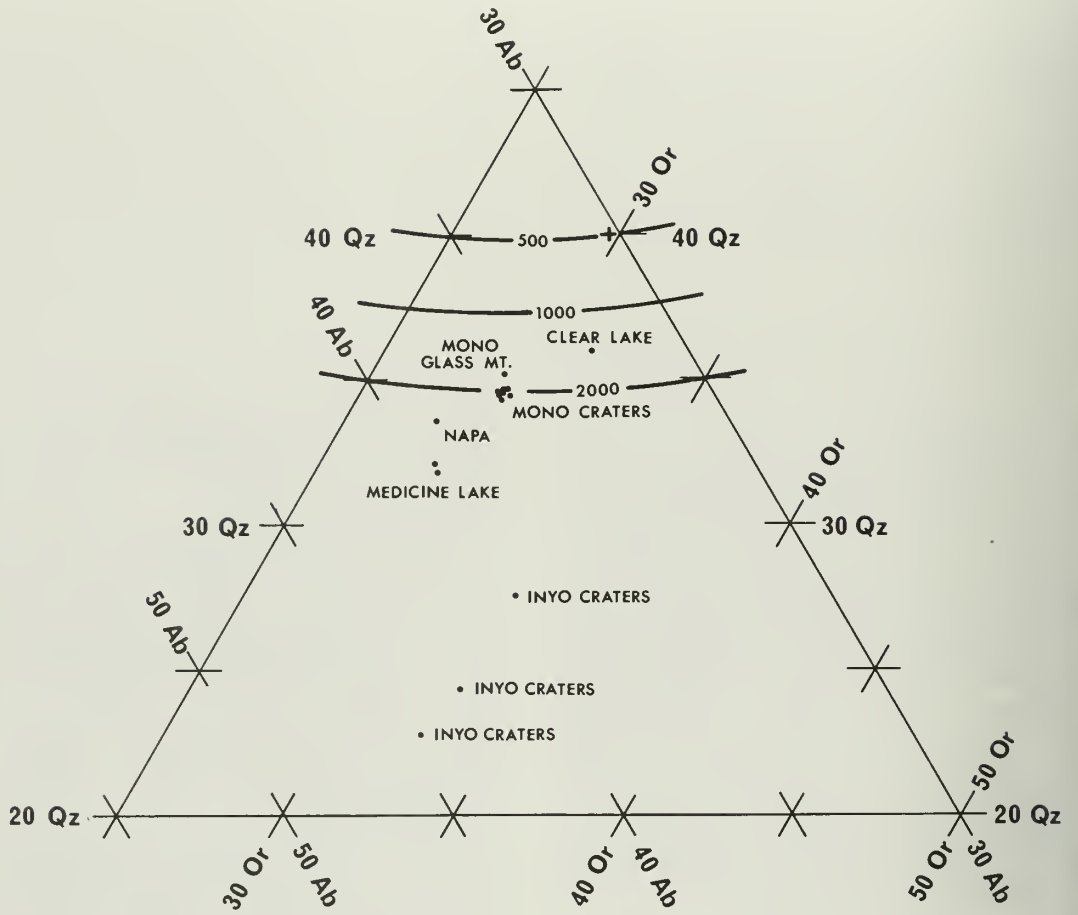


Figure 1. Salic Normative Constituents of Obsidian and Pumice. The constituents (less anorthite) of the analyzed obsidian and pumice (Carmichael, 1967; table 1) are plotted in the system $NaAlSi_3O_8$ (Ab) · $KAlSi_3O_8$ (Or) · SiO_2 (Qz). This diagram is the enlarged central part of the complete system (Tuttle and Bowen, 1958); parts of the boundary curves at 500, 1,000 and 2,000 bars water vapor pressure are shown, together with the ternary minimum (crass) at 500 bars.

Curtis and R. F. Heizer kindly contributed specimens, and the National Park Service allowed the second author (Carmichael) to collect specimens in Lassen National Volcanic Park and Crater Lake National Park.

METHODS OF INVESTIGATION

The centers of Quaternary volcanicity sampled are shown in figure 2 and the individual specimen localities are given in appendix 2. The x-ray fluorescence analyses, the results of which are reported in table 1, were determined (by R. N. J.) with a Norelco (Philips) Universal Vacuum Spectrograph under the analytical conditions summarized in appendix 3. Appendix 1 is a brief summary of the rapid scan technique utilized for stratigraphic and archaeologic applications. Complete analyses (major oxides) have previously been reported for 16 of the rock samples listed in table 1 (Medicine Lake: 1 and 3, Inyo: 16, 18, and 21, Mono: 29, 30, 31, 32, 33, 35, and 36, Clear Lake: 45, and Lassen: 48, 49, and 50) (Carmichael, 1967). As mentioned above, the range of major element compositions of the samples is quite n r hence the variation in the calculated relative m s sorption values likewise is small, the range bein per cent at wavelengths shorter than the i n absorption edge and ± 1 per cent at each of the v lengths longer than the iron K absorption edg cordingly a general (average) matrix absorptio v relative to that of the standard (G-1 or W-1, as p priate) was applied to obtain the values listed i t 1. The calculated theoretical limits of detection based upon a 95 percent confidence level (Ca and Thatcher, 1962) for the conditions of thes a yses are as follows:

Nb, Zr, Y, Sr, Rb, Ga, Zn, Cu, Ni, Co	
Th, Pb, Mn, Nd, Pr, Ti	
Ce, La, Ba	1

In the range of compositions reported in tabl 1 2 sigma (95%) statistical confidence level is ver c to plus or minus the value of the above detectio i with the exception of values above 500 ppm f Ti, and Ba, where a value of ± 1 percent f amount reported is more realistic.

samples were taken of the freshest material of f the sampled extrusive rocks; this was usually y rock, but where pumice was closely associated, as fine airfall material, it was also sampled. Each two pairs of non-porphyritic obsidian and pumble 1, nos. 2 and 3; 32 and 33) have an almost al composition, and cannot be distinguished one from the other. Any possible variation in composition of a single lava flow was largely ignored (apart from conspicuous field variants) after it was found that grab samples from seven separate extrusions of the Mono chain of craters could not be distinguished one from the other (table 1).

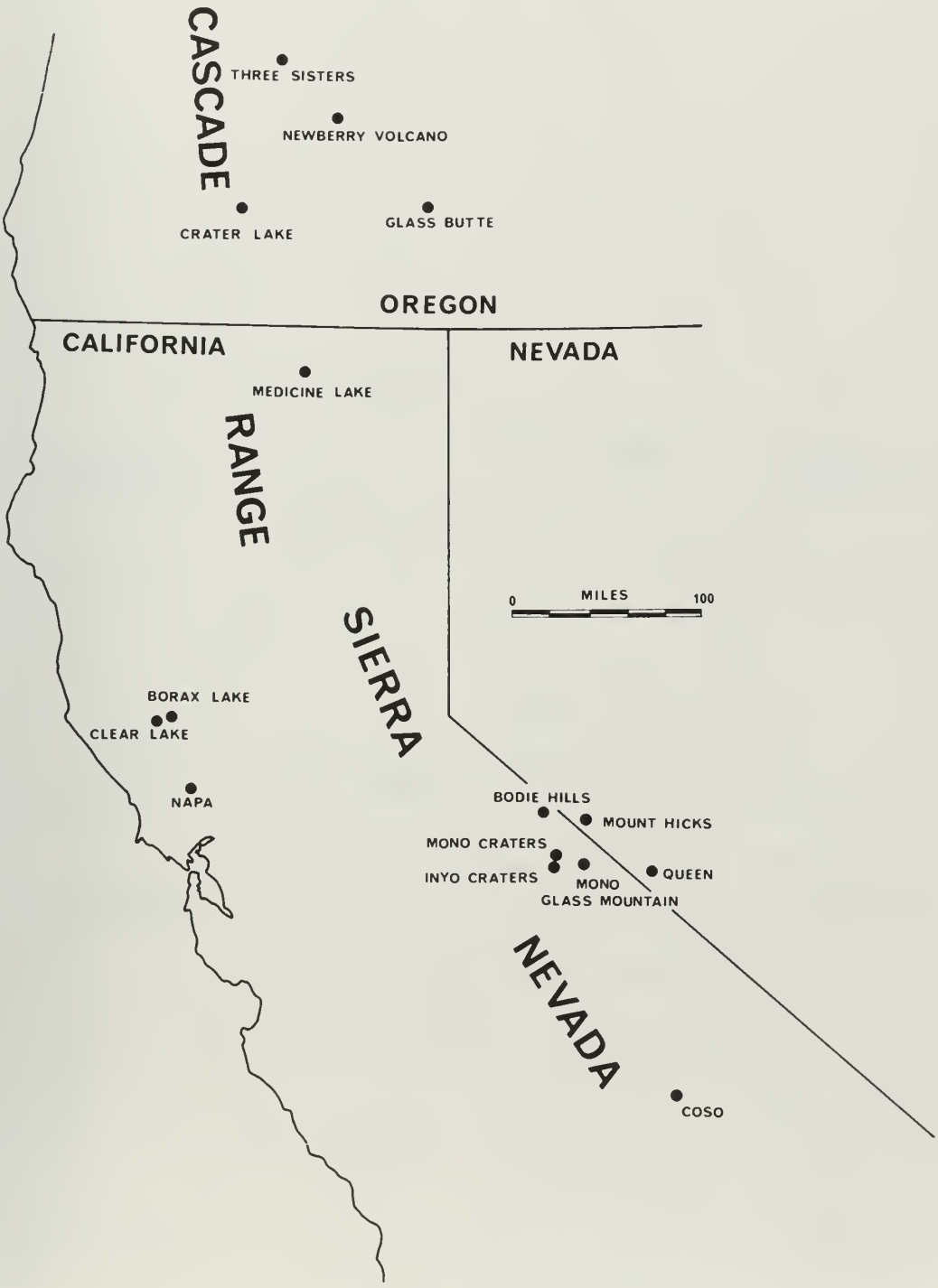
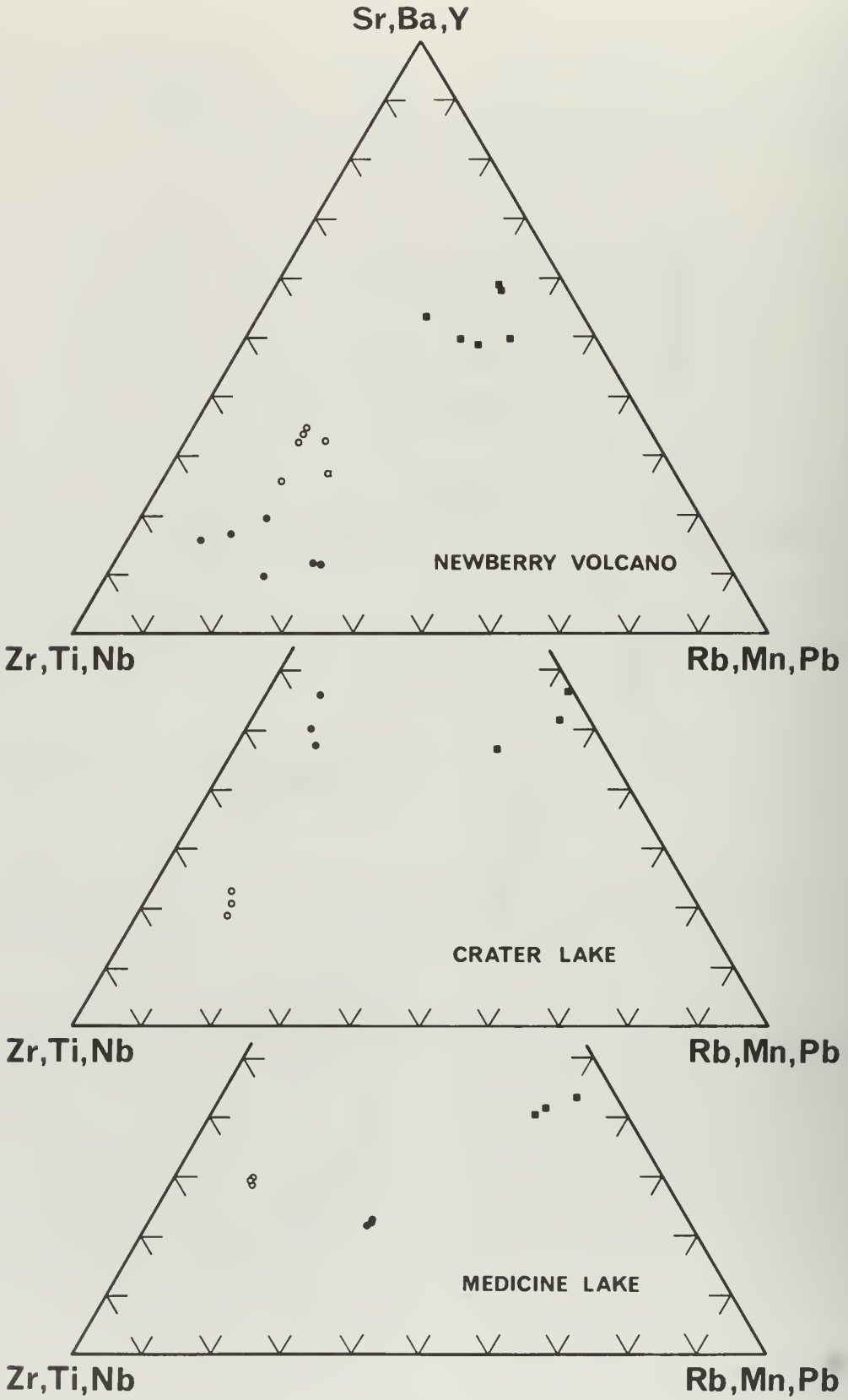
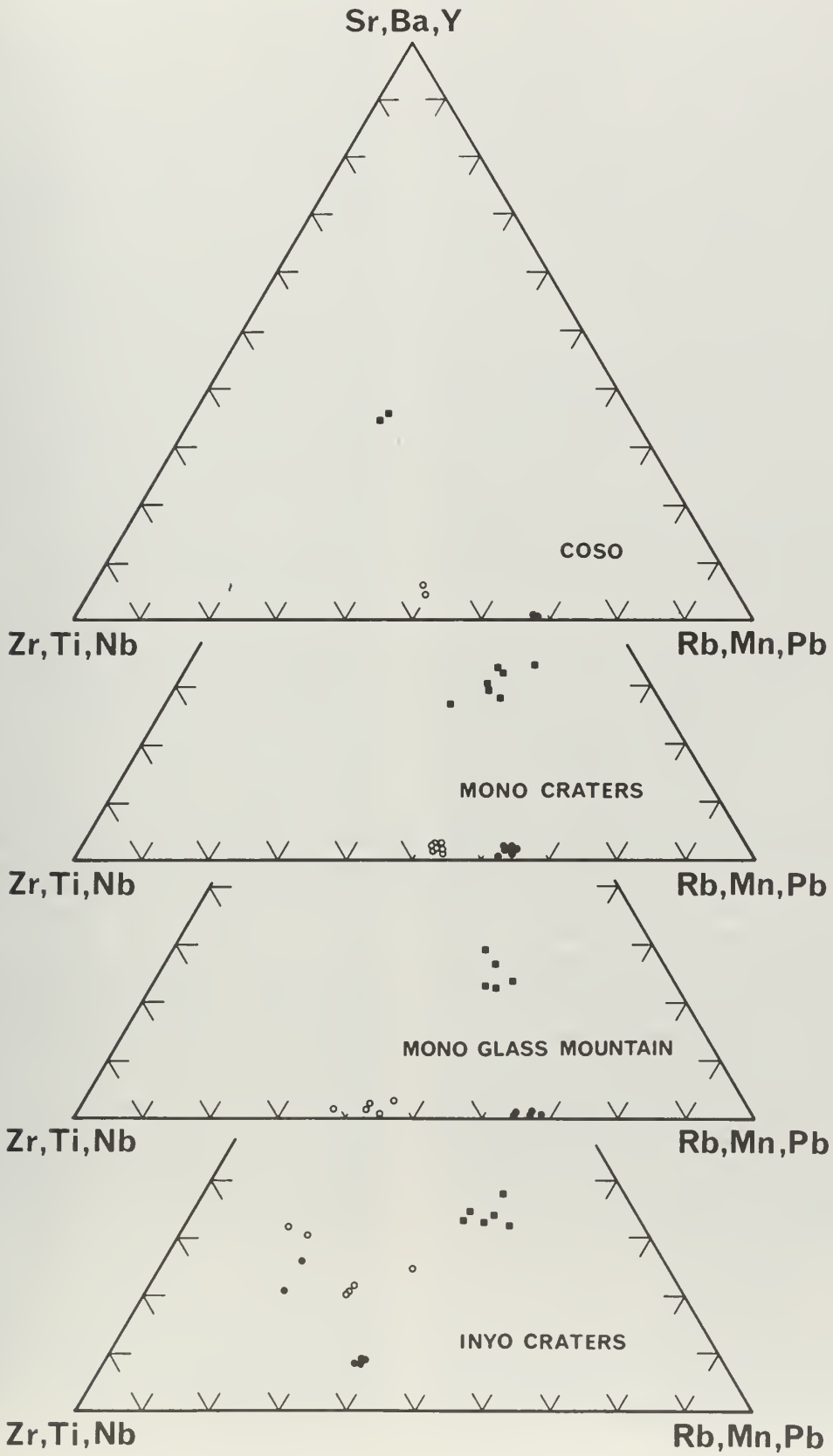


Figure 2. Lacatians af Sampled Centers. The map shaws centers of Quaternary acid valcanism in the western United States.



Figures 3 and 4. Relative Cancentrations of Three Graups of Elements, Coscade Range (above) and Mono Basin Area (right). Three combinations of three elements are shown in each triangle: filled circles represent the relative cancentrations af the elements Sr, Zr and Rb, open circles, Ba, Ti and Mn, and filled squores, Y, Nb

and Pb. Each triangle shaws data for samples fram a single valcanic center. Much greater scatter appears in acid valcanic racks fram Newberry Valcana than in those fram the Mana Craters. The acid volcanic racks from Mono Craters and Mano Glass Mauntain are difficult, if nat impossible, ta distinguish chemically (table 1).



ANALYTICAL RESULTS

Detailed perusal (or statistical analysis) of the analytical results given in table 1 would convince the reader that with one exception, the (randomly obtained) samples from each of the volcanic centers (fig. 2) have a characteristic pattern of trace element concentrations, which can therefore be used to "fingerprint" their geographical source. This fingerprinting is shown diagramatically in figures 3 and 4 in which the *relative* variation of groups of elements having appreciable *absolute* variation throughout the samples from two regions have been plotted. We have found it convenient to group together those elements whose analytical lines are spectrally adjacent, as this facilitates the use of relative x-ray line emission intensities for the nondestructive rapid-scan identification of artifacts. The following three groups of elements have been used and the approximate factor by which each of them varies throughout all the samples (table 1) is given in parentheses; Rb(6), Sr(70), and Zr(40); Mn (5), Ba(130) and Ti(10); Pb(3), Y(6) and Nb(11). It should be noted that the plotted points in figures 3 and 4 are *relative* concentrations of the three chosen elements, so that any variation in their absolute amounts is another factor which may be used to identify or characterize the source material; for example, obsidian with 10 ppm each of Rb, Sr and Zr will plot in the same position as obsidian with 100 ppm of each.

Elements which show little variation in these acid extrusive rocks, such as Ga, Cu, Ni and Co and to a lesser extent Th (table 1), cannot be used to fingerprint the eruptive centers. The three elements Cu, Pb and Zn, which have been used previously to characterize pitchstone and obsidian from various volcanic centers (Carmichael, 1962), have not been used here, as in the identification of possible eruptive sources for pumice in sediments, it seems that pumice fragments are habitually separated from the sedimentary material by sieving through brass screens. The light rare earths (La, Ce, Pr and Nd) do vary to a small extent in these samples (table 1), but as the ratio of one to the other is virtually constant in these rocks, it is necessary only to determine La (most easily determined) or Ce (which is the most abundant) in order to characterize these samples. Cr and V are near or below the detection limit (10 ppm) in all the analyzed samples.

As noted above, there are only two groups of samples which are virtually indistinguishable one from the other; these are the extrusive materials of Mono Craters and those of (Mono) Glass Mountain 20 or so miles toward the east in Mono basin. It is possible that Zn (table 1) is a telltale element in making what is at best a rather dubious distinction.

DISCUSSION

Petrology

Geologists may not be surprised that the acid extrusive rocks from each of the volcanic centers are unique in composition. Geologists would consider this uniqueness a reflection of variation in either the source material from which the acid magma has been le or the physico-chemical process by which it generated, or some combination of the tv isotopic evidence relevant to the origin or ge of the samples discussed in this paper is rather Hedge and Walthall (1963) have shown a obsidian (and pumice) from Glass Mountain, Me Lake (table 1, no. 3) has an Sr^{87}/Sr^{86} ratio clo identical to, those of oceanic basalts, a fact tha suggest that this acid lava has not been g by any process involving old sialic material. for O^{18}/O^{16} for this lava presented by Taylo supports this conclusion; he suggests that cru tamination is also not substantial in the gener the acid lavas of Newberry Volcano, Oregon (a nos. 8–13). However the obsidian at Clear Lak 1, nos. 44–45) is abnormally enriched in O^{18}, su tive of sialic assimilation, whereas the O^{18}/O^{16} for the acid lavas of Mono Craters (table 1, o 36) and Coso Junction (table 1, 27 and 28) a mediate between those of the Clear Lake obsi those of Medicine Lake. In summary, the isoto suggest that there is no common origin for rocks discussed in this account. However, in a gous trace-element study of Icelandic pitchst obsidians which Moorbath and Walker (19 shown to be uncontaminated by radiogenic st it was concluded that "acid magma available fr tion in Iceland, as represented by the pit shows little variation in composition throug haps as much as 60 million years" (Carmicha

Within the Mono basin (Gilbert and othe to the east of the Sierra Nevada (fig. 2), the cene to Recent acid extrusions show a con variation in composition which is in many wa pected. To the south of Mono Lake there is of fine-grained acid lava flows (Carmichael, a gentle, often coalescing, crescentic pattern 1966), which range in age from 1300 years to mately 30,000 years (Friedman, 1968); this extrusions of virtually identical composition is called the Mono Craters. Two or three mil south of the Mono chain, there is a series of e (Mayo and others, 1936) which lie on the of the trend of Mono Craters; this group, Inyo Craters, arbitrarily includes (Mayo an 1936) one extrusion (Wilson Butte) which ically and petrographically identical with tho Mono Craters, with which it is hereafter whereas the remainder of the Inyo Craters different. They are distinctive in gross co (fig. 1; Carmichael, 1967) from the lavas of t Craters and are of highly variable aspect, be coarsely porphyritic with abundant cognate i even when fine grained, the lavas are distin ferent in composition from those of Mon (fig. 4) just a few miles to the north. An or so miles to the east in the Mono basin, the obsidian of Glass Mountain (0.9 million yea bert and others, 1968) is virtually identical position with those of Mono Craters (tabl no really definite trace-element criteria can to distinguish the acid lavas from the two

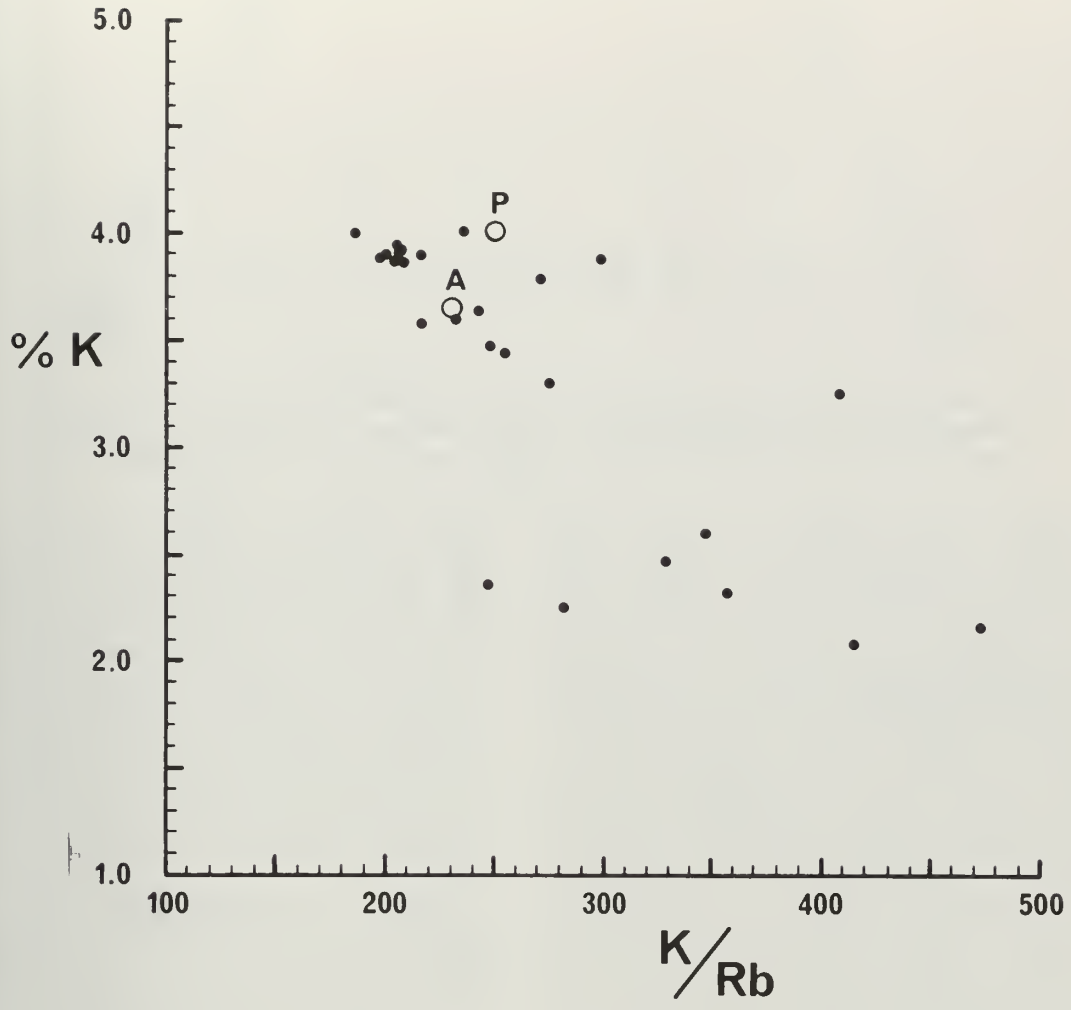


Figure 5. Percent of K Compored With Rotio K/Rb. Percentoges ore by weight for the anolyzed rocks of toble 1. A represents the average of Arran (Scotland) pitchstone (Carmichael ond McDonald, 1961); P represents the averoge of pantelleritic obsidian (Butler and Smith, 1962).

w seems conclusively established that the ratio varies with the concentration of K in igneous ries (Taubeneck, 1965; Abbott, 1967). In figure values of K/Rb (table 1) have been plotted K and show the higher, and more variable, f K/Rb of the dacites in contrast to those of olites. Also shown in figure 5 are the average alues of the Arran (Scotland) pitchstone (Car- and McDonald, 1961) and the peralkaline itic rhyolite (Butler and Smith, 1962); there o be little variation of the ratio K/Rb in acid undoubted diverse chemistry and origin.

Stratigraphy

a significant proportion of the total volume id volcanic eruption is represented in the air- and pumice which, depending upon the winds force of eruption, may be scattered over a a. Thus any ash or pumice horizon is of considerable potential value as a stratigraphic marker if it may be reliably identified over a wide area. Wilcox (1965) has summarized the various techniques that may be used to characterize an ash deposit (particularly of acid composition) and thus identify the source or extent of the eruption; in this respect, we would like to offer some preliminary x-ray fluorescence results to the identification of an ash eruptive source.

Perhaps the best known and most widely distributed of the ash horizons in the United States is the Pleistocene Pearlette Ash Member of the Sappa Formation and correlative ash beds, which have yet to be convincingly traced to a volcanic center. Wilcox (1965) has shown the distribution of the Pearlette and ash beds considered to be Pearlette; they are found throughout the Great Plains (type locality in Kansas), Colorado, Utah, Wyoming and Nevada, and if all these occurrences are one and the same ash bed, then the enormous area covered indicates an eruption of

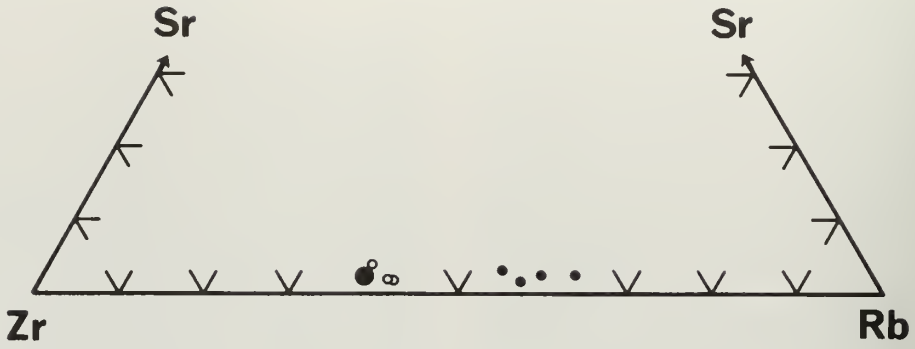


Figure 6. Explaratary Data on Pearlette Ash Samples fram Kansas, Utah and Nevada. Open circles represent Pearlette ash and small filled circles represent Yellawstane Park acid valcanic racks (including Na. 47, table 1). Large filled circle represents pumice samples fram Island Park Caldera, Idaha.

extreme violence. Three specimens of alleged Pearlette ash (kindly provided by G. H. Curtis) from Kansas, Nevada and Utah all contain similar proportions of the diagnostic trace-elements noted before (page 22) together with unusually large amounts of Nb. This immediately eliminates many of the Cascade volcanic centers as a possible eruptive source; a sample of obsidian from Obsidian Cliff, Yellowstone National Park has similarly high Nb (table 1, Cam 147), but the proportions of Rb, Sr and Zr are distinctly different from those of the ash samples. If all the Yellowstone acid extrusions had a composition similar to that of the obsidian (fig. 6), Yellowstone Park would seem to be precluded as the eruptive source of the Pearlette. However, several specimens of acid volcanic rock from the nearby Island Park, Idaho caldera (Hamilton, 1965) (again kindly provided by G. H. Curtis) matched the trace-element pattern of the Pearlette ash (fig. 6). While this locality is not to be taken as conclusively established as the eruptive source of the Pearlette, the analysis provides an example of the x-ray fluorescence technique as a reconnaissance tool and its potential in quickly eliminating several geologically possible sources. Obviously, more detailed and thorough analyses are necessary to establish the eruptive origin of the Pearlette and the number of eruptions or volcanic centers that produced the ash.

Archaeology

Indians in many of the counties of northern California used obsidian as a raw material for the manufacture of artifacts, particularly weapon points. As the geographical locations of sources of obsidi able for artifact manufacture are widely s throughout the region of northern California, and Oregon, it was proposed to the authors identification of the source material used to m weapon points would be interesting and poss formative (cf. Parks and Tieh, 1966). Repres samples of arrowheads from three counties in n California (one on the eastern side of the Nevada) were provided by R. F. Heizer of partment of Anthropology, Berkeley, and we lyzed with a non-destructive rapid-scan techni appendix 1).

Of the 105 arrowheads collected from Conti County (fig. 7), all but three had closely simi portions of Rb, Sr and Zr (fig. 7), and they r the obsidian from the eruptive center in Napa The arrowheads collected from nearby Colusa (fig. 7) split into two groups analytically: 46 had the same proportions of Rb, Sr and Zr as th County obsidian source material (fig. 7), whe samples had distinctly different proportions elements, an analysis that indicates a source o ian raw material from a locality near Bora (fig. 7). The arrowheads collected in Alpine across the Sierra Nevada, were analyzed and i a source of obsidian raw-material in nearby County (fig. 7); this same source material also r the three "misfits" from Contra Costa Count. rapid scan technique, providing one (reconna analysis every five to seven minutes, has produc to support other anthropological evidence of trade across the Sierra Nevada.

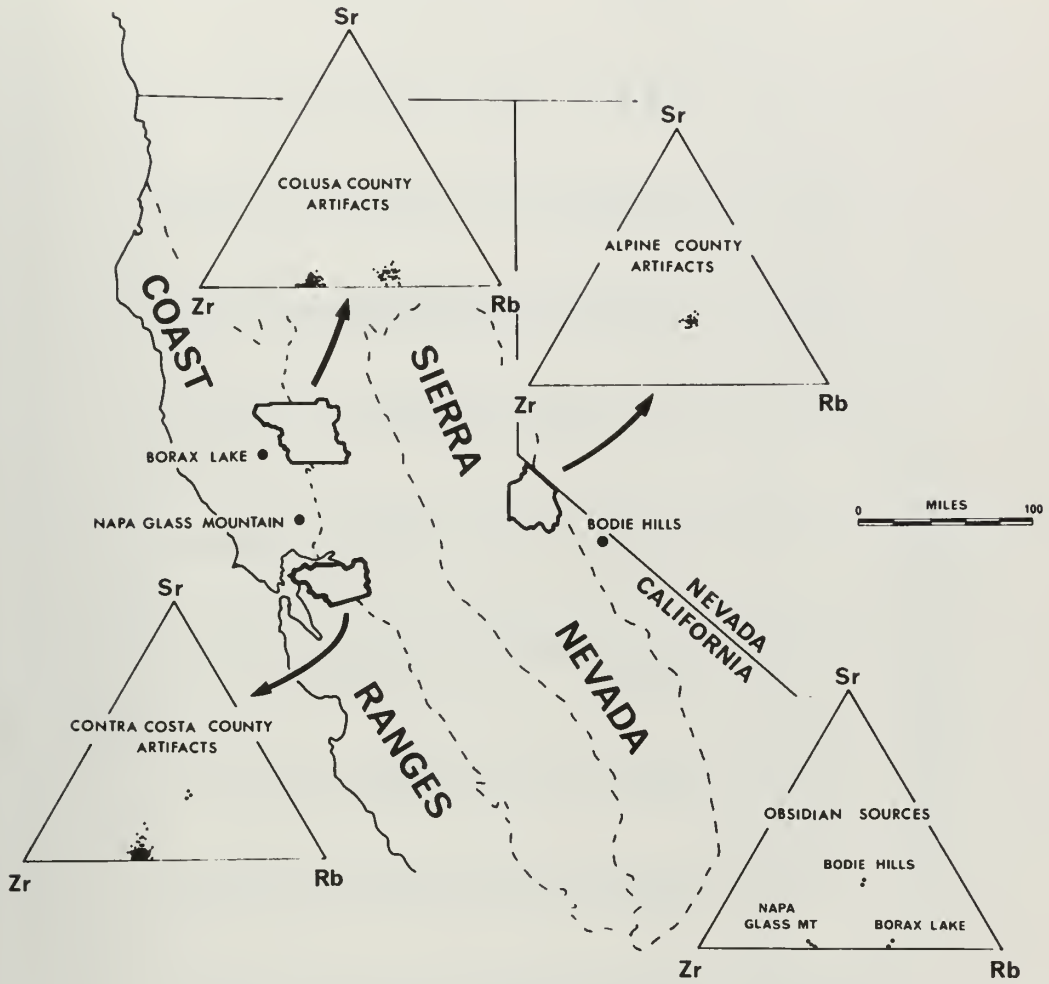


Figure 7. Rapid Scans for Sr, Zr and Rb in Obsidian Artifacts from Three Counties. The results of scans are plotted for artifact samples from Calusa, Contra Costa and Alpine Counties, California. Each point represents the relative SrKα, ZrKα and RbKα intensities observed for one artifact. Also shown are relative intensities for obsidian samples from the indicated source localities.

Table 1. Analyses of Silicic Volcanic Rocks
(K in weight percent; all others in parts per million)

	Medicine Lake, California			Glass Butte, Oregon	Crater Lake, Oregon			Newberry Volcano, Oregon						Three Sisters, Oregon
	1 (Cam 49)	2 (Cam 64)	3 (Cam 66)	4 (Cam 146)	5 (Cam 124)	6 (Cam 125)	7 (Cam 126)	8 (Cam 129)	9 (Cam 130)	10 (Cam 131)	11 (Cam 132)	12 (Cam 133)	13 (Cam 134)	14 (Cam 137)
K	3.64	...	3.60	3.26	2.16	2.08	2.32	...	...	3.47	2.47	3.44	3.30	2.60
Ti	1700	1785	1745	520	2825	3000	2600	2150	1495	1400	1800	1400	1420	1885
Mn	325	340	350	405	540	570	455	660	480	460	845	470	605	490
Co	15	15	15	20	25	30	20	25	35	25	25	20	25	20
Ni	5	5	5	5	5	5	5	5	10	5	5	5	5	5
Cu	10	5	10	5	10	15	15	5	5	5	<5	5	5	10
Zn	25	25	25	30	40	40	35	50	45	40	70	40	55	35
Ga	10	10	15	15	15	15	15	15	15	15	20	15	15	15
Rb	150	155	155	80	55	50	65	95	40	140	75	135	120	75
Sr	105	105	105	30	295	360	270	100	60	55	85	55	50	220
Y	25	20	20	45	25	20	20	40	30	30	35	40	45	15
Zr	215	220	215	95	240	235	235	315	285	280	350	280	355	180
Nb	5	5	5	10	<5	5	<5	5	10	10	5	15	20	5
Ba	860	870	850	1300	860	820	900	960	930	940	970	980	960	840
La	30	30	30	40	30	30	30	40	40	40	40	40	50	30
Ce	60	60	60	90	60	50	50	70	70	70	80	80	80	50
Pr	5	5	5	5	<5	5	<5	10	5	10	5	5	5	5
Nd	20	25	20	25	25	20	20	30	25	25	30	30	30	20
Pb	30	25	25	10	20	15	20	20	20	25	20	25	20	10
Th	15	20	20	10	15	5	5	15	25	20	10	25	15	<5

Table 1—Continued

	Inyo Craters, California							Mono Glass Mountain, California					Coso Junction, California	
	15 (Cam 80)	16 (Cam 81)	17 (Cam 83)	18 (Cam 86)	19 (Cam 87)	20 (Cam 90)	21 (Cam 93)	22 (Cam 139)	23 (Cam 140)	24 (Cam 141)	25 (679-406)	26 (Cam 144)	27 (Cam 150)	28 (Cam 151)
K	...	3.58	...	3.79	...	...	3.88	3.89	...	4.01	3.93	...	...	...
Ti	855	805	825	1485	510	2160	2005	440	445	505	475	480	310	315
Mn	525	505	495	575	505	490	600	390	360	305	360	295	335	335
Co	15	15	10	15	15	15	15	20	20	20	15	10	15	15
Ni	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Cu	<5	<5	<5	<5	<5	5	<5	<5	<5	<5	5	5	5	<5
Zn	40	40	40	45	40	35	45	25	25	20	35	20	60	55
Ga	15	15	15	15	15	15	15	15	15	15	15	15	20	20
Rb	160	165	165	140	165	120	130	195	190	170	190	170	245	240
Sr	40	40	35	115	40	255	165	<5	<5	<5	<5	<5	<5	5
Y	25	25	25	20	25	15	25	25	25	20	30	25	50	55
Zr	25	25	240	295	235	190	340	85	90	90	95	90	115	115
Nb	15	20	20	15	15	10	10	30	25	20	25	25	55	55
Ba	360	370	330	890	330	840	1220	30	10	10	20	10	40	40
La	90	90	90	70	80	50	60	30	30	40	40	40	20	20
Ce	160	150	160	140	160	70	110	70	60	70	70	80	60	60
Pr	10	10	15	10	10	<5	10	10	<5	5	5	5	5	5
Nd	40	40	40	40	40	20	30	25	20	20	25	25	20	20
Pb	35	30	30	30	30	35	25	50	50	40	45	45	40	45
Th	20	20	15	20	30	20	20	30	40	25	25	30	20	30

Table 1—Continued

	Mono Craters, California								Mt. Hicks, Nevada	Queen, Nevada	Antelope Valley, California	Bodie Hills, California	
	29 (Cam 73)	30 (Cam 95)	31 (Cam 99)	32 (Cam 103)	33 (Cam 104)	34 (Cam 105)	35 (Cam 108)	36 (Cam 110)	37 (679-438)	38 (679-439)	39 (679-436)	40 743-306	41 743-307
K	3.87	3.90	3.87	3.90	3.91	...	3.92	3.90	...	...	...	...	...
Ti	375	390	370	400	375	390	390	395	660	725	925	640	630
Mn	440	445	445	450	445	450	450	455	475	890	355	360	620
Co	10	15	10	10	15	10	15	10	5	10	10	5	5
Ni	<5	5	<5	<5	5	5	5	<5	...	...	5	<5	<5
Cu	<5	<5	<5	<5	<5	<5	<5	<5	...	...	<5	<5	<5
Zn	40	35	35	40	40	40	40	35	30	50	30	20	20
Ga	15	15	15	15	15	15	15	15	15	20	15	10	10
Rb	185	195	190	180	190	195	190	195	165	180	145	195	195
Sr	5	5	5	<5	5	5	5	5	25	15	90	95	90
Y	25	30	25	30	30	25	25	25	15	20	15	15	10
Zr	100	105	110	110	110	105	105	105	80	135	180	95	100
Nb	20	15	15	20	20	20	20	30	30	50	10	10	15
Ba	20	10	10	20	10	20	20	20	100	80	1020	590	490
La	30	30	30	40	30	30	30	35	40	40	50	45	40
Ce	50	50	50	60	60	60	60	60	70	80	70	50	55
Pr	<5	<5	<5	5	10	5	<5	<5	50	10	<5	5	5
Nd	20	20	20	25	25	20	20	20	20	30	20	20	10
Pb	40	45	40	40	40	45	40	40	55	40	45	35	35
Th	30	35	30	25	30	25	25	20	25	30	10	25	15

Table 1—Continued

	Napa, California		Clear Lake, California		Borax Lake, California	Yellowstone Park, Wyoming	Lassen Park, California		
	42 (Can 112)	43 (Can 113)	44 (Cam 116)	45 (Cam 118)	46	47 (Cam 147)	48 (Cal. 13)	49 (Cal. 19)	50 (L. 118)
K	3.76	...	...	4.00	...	...	...	...	...
Ti	520	540	1520	1545	825	540	...	...	...
Mn	190	200	230	230	240	235	...	...	...
Co	15	15	15	15	10	10	...	...	...
Ni	5	5	5	5	10	10	...	...	...
Cu	10	5	5	5	<5	5	...	...	...
Zn	55	50	25	20	45	80	...	...	...
Ga	15	15	10	15	20	20	...	...	...
Rb	190	200	215	215	215	250	80	90	80
Sr	5	5	65	65	15	<5	330	300	340
Y	45	40	30	30	40	90	10	15	5
Zr	240	230	185	180	90	170	130	140	125
Nb	10	10	10	5	15	65	...	...	...
Ba	420	430	610	650	80	50	805	880	855
La	40	40	40	40	40	80	30	30	30
Ce	80	70	80	70	60	130	...	...	...
Pr	5	5	10	10	<5	10	...	...	...
Nd	30	25	30	30	25	50	...	...	...
Pb	50	50	45	50	50	40	...	...	...
Th	25	15	25	30	10	45	...	...	...

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APPENDIX 1

Rapid Scan Technique

In addition to precise quantitative chemical analyses (table 1), the x-ray fluorescence technique can provide very rapid semi-quantitative determinations of many elements in low concentration. Commonly the most convenient technique is a rapid scan of the s region of interest, for example, the NbKα, YKα, SrKα, RbKα, ThLα, and PbLβ region angstrom to 0.99 angstrom), in which the ZrKα, SrKα, and RbKα intensities are parti useful for plotting natural glass samples (see fig The sample (up to 1¼″ in diameter for the cu used sample cup) is placed in the cup in the for flake or artifact (obsidian), rock chip (pumice, lite, etc.), loose grains or powder (volcanic ash) the form of a specially prepared pellet for a such as those given in table 1. In spite of variat the effective sample surface of randomly broken or loosely packed grains, *relative* intensities very precisely determined. Quite precise "ab concentrations may also be obtained in many a cal situations by using the primary beam (cont plus characteristic radiation of the target m scattered from the sample to standardize the ef intensities (chart recorder deflection) from san sample by varying the spectrograph tube (ma).

APPENDIX 2

Sample Localities

Medicine Lake, Modoc County, northern Calif

Cam 49. Porphyritic obsidian, Little Glass tain, Sec. 13, T43N, R2E, MDBM

Cam 64 and Cam 66. Pumice and obsidian tively, Glass Mountain, Sec. 33, R4E, MDBM.

Mono Craters, Mono Basin area, California

Cam 73. Rhyolite, Hill 8060 immediately east of Devil's Punchbowl, Sec. 3 R27E, MDBM.

Cam 95. Rhyolite of Wilson Butte, on U.S. way 395, Sec. 8, T2S, R27E, MD

Cam 99. Rhyolite, Hill 8044 immediately west of Devil's Punchbowl, Sec. 3 R27E, MDBM.

Cam 103 and Cam 104. Pumice and obsid spectively, north of pumice mi 28, T1S, R27E, MDBM.

Cam 105. Obsidian extrusion south of pumic by headframe, Sec. 28, T1S, MDBM.

Cam 108. Obsidian extrusion lobe by U.S. way 120, Sec. 30, T1N, R27E, MD

Cam 110. Obsidian extrusion immediately s Panum Crater, Sec. 19, T1N, MDBM.

Inyo Craters, Mono Basin Area, California

Cam 80, Cam 81, and Cam 83. Porphyriti lite, obsidian, and pumice, respe Glass Mountain, south of Wilso off U.S. Highway 395, Sec. 2 R27E, MDBM.

86 and Cam 87. Porphyritic obsidian and rhyolite respectively, extrusion south of Glass Mountain.

90 and Cam 93. Crystal-rich pumice and porphyritic obsidian, Deadman's Creek, off U.S. Highway 395, Sec. 5, T3S, R27E, MDBM.

Mountain, eastern Mono Basin area, California

139. Obsidian from base of Glass Mountain, Sawmill Meadow, Sec. 16, T2S, R30E, MDBM.

140. Porphyritic obsidian in scree above Cam 139.

141. Obsidian, west edge of Sec. 5, T2S, R30E, MDBM, in road cut.

406. Obsidian with dated sanidine (Gilbert and others, 1968, Table 1, KA-2081), summit of Glass Mountain, Sec. 18, T2S, R30E, MDBM.

Hicks, Mono Basin area

438. Obsidian on east slope of Mount Hicks (Sec. 24, T5N, R29E, MDBM) by roadside in Alkali Valley Aurora Quad., Calif.-Nevada. U.S.G.S. 15′ series.

Mono Basin area

439. Obsidian, 1 mile northwest of Queen, Sec. 17, T1N, R32E, MDBM, White Mountain Quad., U.S.G.S. 30′ series.

pe Valley, Mono Basin area

436. Obsidian in Little Antelope Valley, 2 miles north of Casa Diablo Hot Springs on U.S. Highway 395, Sec. 22, T3S, R28E. See Rinehard and Ross, 1964.

Hills, east of Bridgeport Reservoir, Mono Basin a

306 and 743–307. Rhyolite and obsidian extrusion, east part of northeast quarter of Sec. 21, T5N, R26E, MDBM.

unction, Inyo County, California

150 and Cam 151. Obsidians from extrusion south of ruined house east of U.S. Highway 395, Sec. 12, T22S, R38E, MDBM.

Valley, Napa County, California

112. Obsidian pebbles in ash cone, Silverado Road, south of Glass Mountain Road, St. Helena, Sec. 24, T8N, R6W, MDBM.

Cam 113. Obsidian pebbles in tuff, Silverado Road, north of Glass Mountain Road, St. Helena, Sec. 14, T8N, R6W, MDBM.

Clear Lake, Lake County, California

Cam 116. Porphyritic obsidian, Bottle Rock Road, by stream, Sec. 36, T13N, R9W, MDBM.

Cam 118. Porphyritic obsidian, road cut by northerly track on Bottle Rock Road, Sec. 7, T12N, R8W, MDBM.

Borax Lake, Lake County, California

South of Borax Lake, near Clear Lake, Lake County, California, Sec. 7, T13N, R7W, MDBM.

Crater Lake, Oregon

Cam 124. Dacite of Llao Peak, Rim Drive north of road junction.

Cam 125. Dacite, Rim Drive about ¼ mile north of Cleerwood (Lake) trail.

Cam 126. Obsidian from Cloudcap, near road junction to summit.

Newberry Volcano, Oregon

Cam 129. Obsidian from north shore of East Lake.

Cam 130. Obsidian from south of East Lake.

Cam 131. Older rhyolite between Paulina and East Lake.

Cam 132. Porphyritic obsidian from Paulina Peak.

Cam 133. Obsidian between Paulina and East Lake.

Cam 134. Obsidian from latest obsidian flow.

Three Sisters, Oregon

Cam 137. Southernmost dacite, by road (Century Drive).

Glass Butte, Oregon

Cam 146. Obsidian, scree material by road off U.S. Highway 20.

Yellowstone Park, Wyoming

Cam 147. Celebrated obsidian flow in National Park.

Lassen Park, California

Cal 13. Pre-Lassen dacite (Williams, 1932, p. 300 ff.), Sunflower Flat, Lassen National Volcanic Park, California.

Cal 19. Raker Peak Dacite, Lassen National Volcanic Park, California.

L. 118. Dacite dome of White Mountain, Lassen National Volcanic Park, California.

APPENDIX 3

Summary of X-ray Fluorescence Analytical Conditions

Element	Analytical Line (a)	Analyzing Crystal (b)	Exciting Radiation (50 KV) (c)	Primary Beam Filter (d)	Detector (with Pulse-height discrimination)	Path	Stan (assu va in p
Ti	Kα	LiF (200)	W	—	Flow proportional	vacuum	G-1 (
Mn	Kα	LiF (200)	W	—	Scintillation	air	G-1 (
Co	Kα	LiF (220)	W	—	Scintillation	air	W-1 (
Ni	Kα	LiF (200)	Mo	.001″ Ti	Scintillation	air	W-1 (
Cu	Kα	LiF (200)	Mo	.001″ Ti	Scintillation	air	W-1 (
Zn	Kα	LiF (200)	Mo	.001″ Ti	Scintillation	air	W-1 (
Ga	Kα	LiF (200)	Mo	.001″ Ti	Scintillation	air	W-1 (
Rb	Kα	LiF (220)	W	—	Scintillation	air	G-1 (
Sr	Kα	LiF (220)	W	—	Scintillation	air	G-1 (
Y	Kα	LiF (220)	W	—	Scintillation	air	G-1 (
Zr	Kα	LiF (220)	W	—	Scintillation	air	G-1 (
Nb	Kα	LiF (220)	W	—	Scintillation	air	G-1 (
Ba	Lα	LiF (200)	W	—	Flow proportional	vacuum	G-1 (
La	Lα	LiF (200)	W	—	Flow proportional	vacuum	G-1 (
Ce	$L\beta_1$	LiF (220)	W	—	Flow proportional	vacuum	G-1 (
Pr	Lα	LiF (220)	W	—	Flow proportional	vacuum	G-1 (
Nd	Lα	LiF (220)	W	—	Flow proportional	vacuum	G-1 (
Pb	$L\beta_1$	LiF (220)	W	—	Scintillation	air	G-1 (
Th	Lα	LiF (220)	W	—	Scintillation	air	G-1 (

K Flame photometer (Zeiss PF-5); J. Hampel, analyst.

a. Analytical Lines: Kα lines are utilized for elements Nb and below in atomic number and Lα lines for elements above that. Exceptions are $CeL\beta_1$, which is used because of $BaL\beta_1$ interference at the CeLα wavelength and $PbL\beta_1$-$PbL\beta_2$, which is used for convenience in measurement with Th, Rb, Sr, Y, Zr, and Nb.

b. Analyzing Crystal: For elements Co, Rb, Sr, Y, Zr, Nb, Ce, Pr, Nd, Pb, and Th, a lithium fluoride analyzing crystal ground and mounted in the (220) crystallographic orientation by Isomet Corporation is utilized. This crystal provides greatly increased spectral resolution over that provided by the "normal" lithium fluoride crystal (2d of 2.848 Å compared with 4.028 Å for the (200) orientation) and yields very much higher intensities than the conventional high resolution sys such as quartz and topaz.

c. Exciting Radiation: A molybdenum tube is used t ex the metals Ga, Zn, Cu, and Ni in order to eliminate th p lem of interference by scattered first order primary t g radiation. It is possible, using pulse height discrimina n eliminate approximately 99 percent of the second or r radiation while accepting nearly 80 percent of the es analytical line intensities.

d. Primary Beam Filter: Due to the presence in spec gr tubes of a certain amount of Cu and Ni contamination n target, a titanium filter is placed over the tube wind w trace-element analysis to selectively reduce the inten y these lines emitted from the tube.

ETACEOUS AND EOCENE COCCOLITHS SAN DIEGO, CALIFORNIA *

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ABSTRACT

coliths, the skeletal plates of certain fossil marine were used during geologic mapping of San Diego, rnia, as aids in distinguishing between lithologically Upper Cretaceous and Eocene rock units and in buting to the intercontinental correlation of the units.

INTRODUCTION

per Cretaceous and Eocene rocks of the San coastal plain together comprise a laterally varied sion composed of nearshore-marine shale, sand- and conglomerate.

e Mesozoic rocks are Late Cretaceous in age and correlated by Hanna (1926) with the Chico For- n in northern California and by Milow and Ennis) and Sliter (1968) with the Rosario Formation al (1948) in Baja California. The Cretaceous are well exposed along sea cliffs of the Point Peninsula and in the La Jolla district (fig. 1). xposed Upper Cretaceous section consists of two –a lower unit with an exposed thickness of 500 nd an upper unit with a total thickness of 600 The lower unit is a light olive gray to medium thin-bedded to flaggy siltstone, which contains vish gray and medium gray sandstone laminae ities L1 to L8). The upper unit, which grades rd into a pebble-to-boulder conglomerate, is yel- n gray, medium to coarse-grained, arkosic sand- interbedded with a few light olive gray siltstone

cks of Eocene age, the La Jolla Formation of a (1926), lie directly above the Cretaceous rocks only a slight angular unconformity. Hanna di- the La Jolla Formation into three members—a mudstone and sandstone (his Delmar Sand Mem- an intermediate sandstone (Torrey Sand Mem- and an upper siltstone and sandstone (Rose on Shale Member). Samples collected by us from a's Delmar Sand and Torrey Sand Members were n of coccoliths; all Cretaceous localities of this report are in rocks equivalent to Hanna's Rose Canyon Shale member. The lower 200 feet of the Rose Canyon consists chiefly of olive gray to light olive gray siltstone with some interbeds of fine-grained sandstone. Our Eocene localities are all in this lower part of the member and are believed to be disposed from its base to top as follows: base (localities L9, L11), middle (locality L13), and top (localities L10, L12, L14).

Coccoliths, marine microfossils 1 to 20 microns in diameter, are helpful in determining the ages of the lithologically similar Upper Cretaceous and Eocene strata in the San Diego area. As calcite skeletal plates of abundant unicellular planktonic algal species, coccoliths provide an excellent biostratigraphic guide to open-ocean sediments. Whereas offshore rocks may yield billions of coccoliths per cubic centimeter, nearshore samples generally contain only thousands of coccoliths per cubic centimeter. The smaller assemblages in nearshore rocks are the result of ecologic and sediment-dilution factors.

ACKNOWLEDGMENTS

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SAMPLE PREPARATION

Coccolith samples were collected in conjunction with mapping being done by Kennedy and generally contained sparse assemblages. The samples were prepared by Bukry and Kennedy using the rapid survey technique of M. N. Bramlette (personal communication, 1967).

Several cubic millimeters of chips from different parts of the rock sample are placed at the center of a glass slide. A few drops of water are added and a spatula is used to break up the sediment to form a puddle. The coarse fraction is pushed to one end of the slide with the spatula, and the fine fraction (containing any coccoliths) is allowed to accumulate at the

cript submitted for publication November 1968. Publication au- rized by the Director, U.S. Geological Survey.

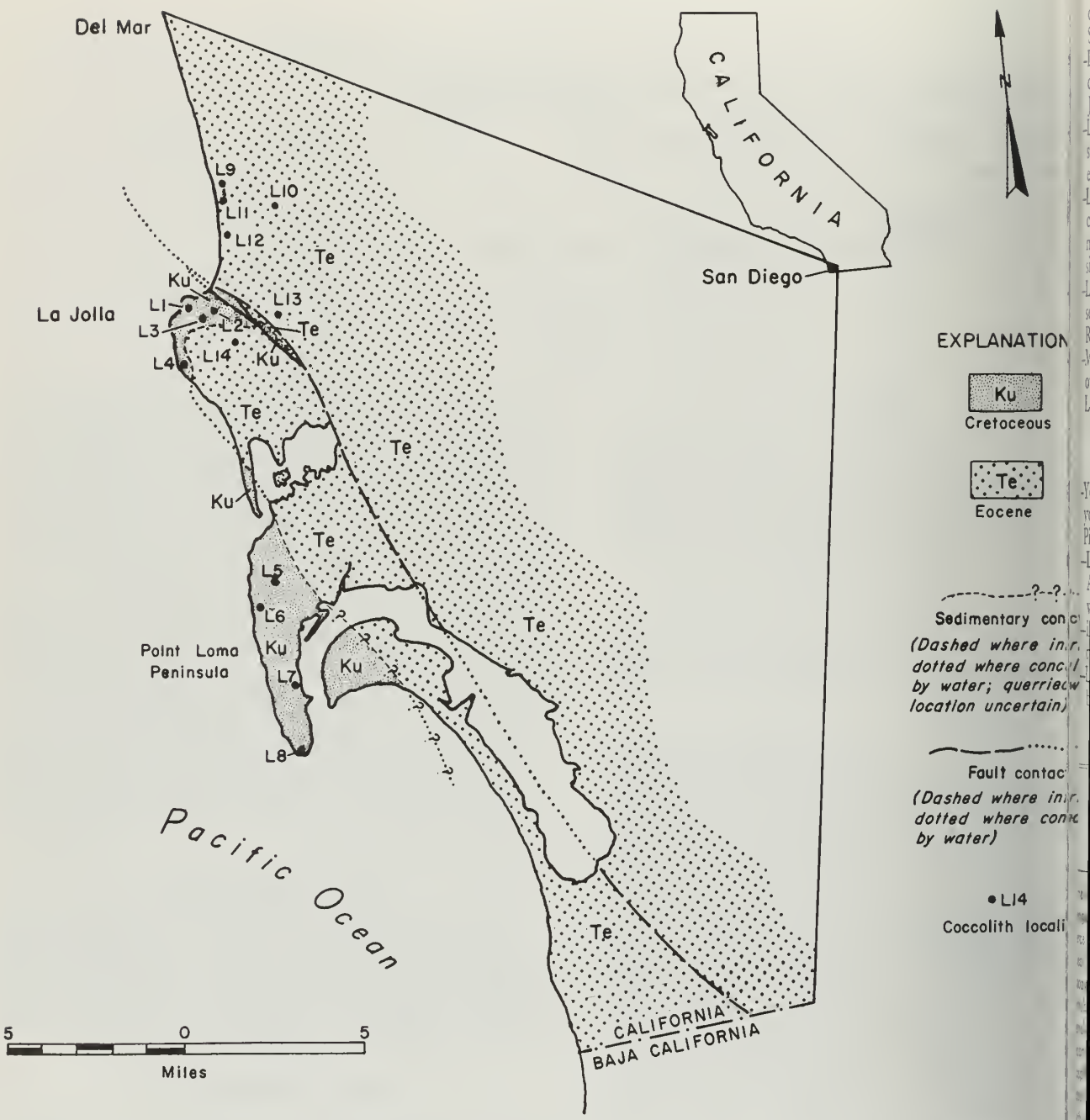

Figure 1. Lacation Map. The map also shows the coccolith localities and the cantact relatians between Upper Cretaceous and Eocen Post-Eocene strata are nat shawn.

other end, as the slide is tilted slightly in that direction. After the water is evaporated by placing the slide on a hot plate, a few drops of mounting medium (Canada balsam or Permount) are placed onto a glass cover slip, which is then inverted and lowered carefully onto the dried fine fraction on the slide. This preparation technique takes about three minutes and permits a microscopic survey of the complete assemblage of any coccoliths present.

LOCATIONS OF COCCOLITH SAMPLE

Cretaceous

L1—Outcrop of yellowish gray medium-g sandstone at the intersection of Little Stre Torrey Pines Road in La Jolla.

L2—Interbedded yellowish gray siltstone in me grained sandstone exposed during excav 800 feet west of the intersection of Via and Via Rialto on Mount Soledad, La Jo

-Interbedded light olive gray siltstone in an outcrop across from 7810 Hillside Drive, Mount Soledad, La Jolla.
-Dark gray siltstone interbed at base point in sea cliff 300 feet south of Bird Rock Avenue, La Jolla.
-Light olive gray siltstone in roadcut near intersection of Banger and Concord Streets, northern Point Loma district.
-Light olive gray siltstone in an artificially excavated slope for parking lot at southwesternmost dormitory at California Western University, Point Loma.
-Light olive gray siltstone in outcrop near intersection of Rosecrans Boulevard and McClellan Road in Fort Rosecrans, Point Loma.
-Medium gray siltstone in sea cliff east and west of U. S. Coast Guard station at the tip of Point Loma.

Eocene

-Yellowish gray silty sandstone in wall of canyon forming the southern margin of Torrey Pines Golf Course, 800 feet east of sea cliff.
—Light gray siltstone in roadcut on Genesee Avenue 2000 feet west of Interstate 5 Freeway.
—Light gray siltstone in sea-cliff gully, 300 feet north of the Salk Institute.
—Light gray siltstone at the parking level at the bottom of University of California access road to beach, 2000 feet north of U. S. Fishery-Oceanography Center Building, La Jolla.
L13—Light gray silty sandstone at Ardath Road southbound onramp to Interstate 5 Freeway.
L14—Yellowish gray siltstone in slope at northeast corner of school ground at the intersection of Nautilus Street and La Jolla Scenic Drive.

CRETACEOUS CORRELATION

All the assemblages of Mesozoic coccoliths collected from Point Loma to La Jolla (table 1) are of Late Cretaceous (late Campanian to early Maestrichtian) age. Correlation of these floras has been aided by the common occurrence of several species of *Tetralithus: T. nitidus nitidus* Martini, *T. nitidus trifidus* (Stradner), *T. aculeus* (Stradner), and *T. pyramidus* Gardet. These are readily identifiable forms and were, in some instances, first described, in the literature, from Tertiary strata into which they had been reworked. However, later studies indicated that they are naturally occurring elements of late Campanian to early Maestrichtian assemblages. In the Taylor Marl of Texas (Gartner, 1968; Bukry, 1969), the upper part of the Demopolis Chalk of Alabama (D. Bukry, unpublished information), and Campanian and Maestrichtian strata of Europe (Deflandre, 1959; Stradner, 1963), *Tetralithus* assemblages occur with an assemblage of other coccolith species—*Arkhangelskiella cymbiformis* Vekshina, *A. parca* Stradner, *Cylindralithus serratus* Bramlette and Martini, *Lucianorhabdus cayeuxi* Deflandre, and *Cretarhabdus decorus* (Deflandre). The

Table 1. Cretaceous Coccoliths at San Diego, California

Coccolith taxa	Sample localities							
	1	2	3	4	5	6	7	8
Heliolithae **Deflandre**								
ngelskiella cymbiformis **Vekshina**	X	X		X	X	X		X
rca **Stradner**	X	X	X	X		X		X
ecillata **Vekshina**			X					
tozygus **Gartner**	X		X	X				
rhabdus conicus **Bramlette and Martini**		X		X				
nulatus **Bramlette and Martini**	X	X	X	X				X
corus **(Deflandre)**	X		X					
osphaera ehrenbergi **Arkhangelsky**	X	X	X	X		X		X
dralithus serratus **Bramlette and Martini**		X	X					X
ithus turriseiffeli **(Deflandre)**	X	X		X				
cosphaera cretacea **(Arkhangelsky)**	X	X	X	X	X	X		X
naueria barnesae **(Black)**	X	X	X	X	X	X	X	X
discus **Bramlette and Martini**	X		X	X				X
Ortholithae **Deflandre**								
dosphaera **sp. cf.** B. africana **Stradner**	X							
orhabdus cayeuxi **Deflandre**	X							X
rhabdulus decoratus **Deflandre**		X		X				
decussata **Vekshina**	X	X	X	X	X	X	X	X
thus aculeus **(Stradner)**	X	X	X	X		X		X
dus nitidus **Martini**	X	X	X	X	X	X	X	X
dus trifidus **(Stradner)**	X	X	X	X	X	X	X	X
midus **Gardet**	X	X	X					

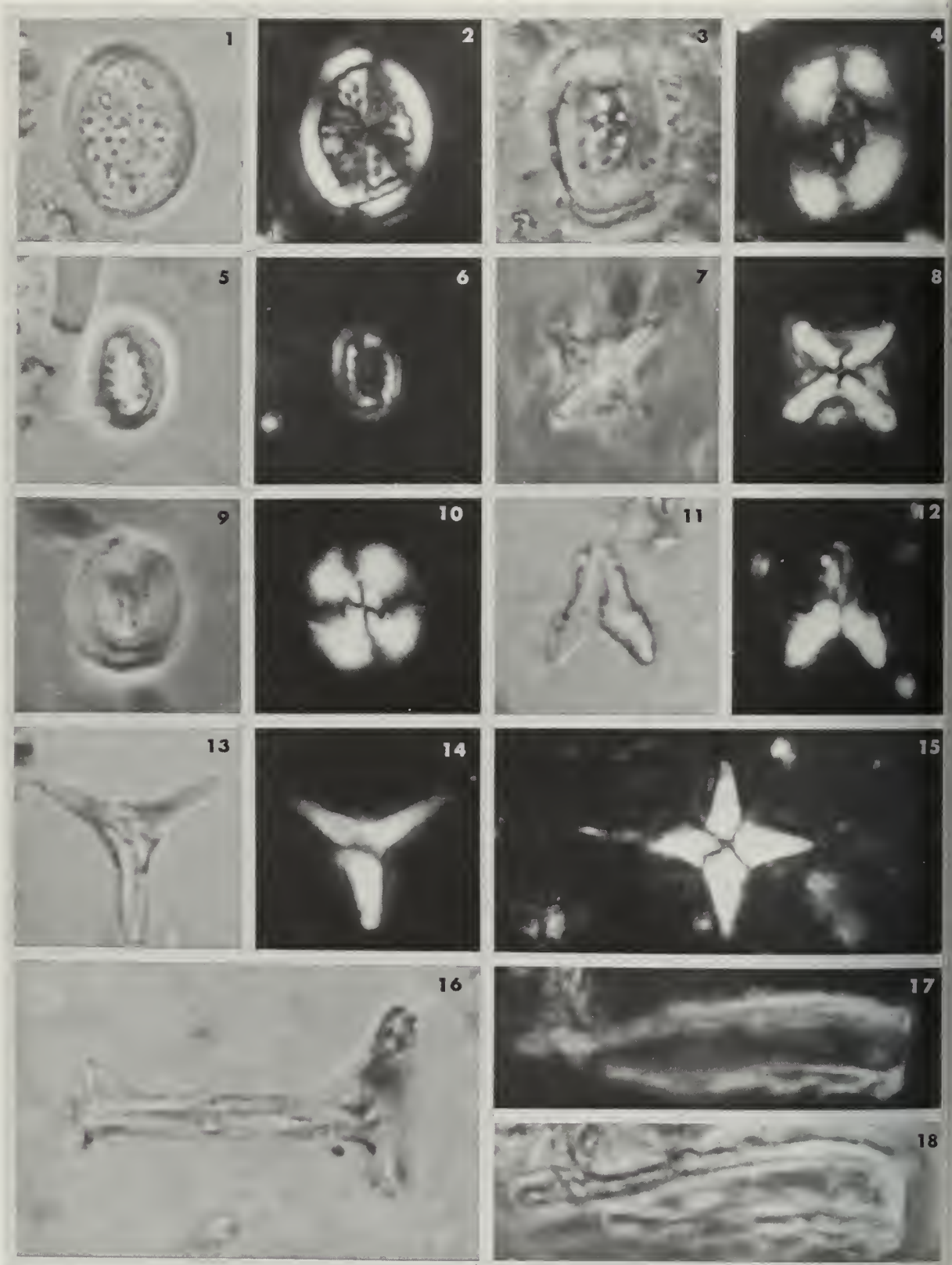
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Figure 2. Cretaceous Coccaliths at San Diego, California (all magnifications ×2500).

1–2 *Arkhangelskiella cymbiformis* Vekshina
1 L2, ordinary light.
2 L2, cross-polarized light.
3–4 *Arkhangelskiella parca* Stradner
3 L1, phase-contrast light.
4 L1, cross-polarized light.
5–6 *Cribrosphaera ehrenbergi* Arkhangelsky
5 L8, phase-cantrast light.
6 L8, cross-polarized light.
7–8 *Micula decussata* Vekshina
7 L8, phase-cantrast light.
8 L8, cross-polarized light.
9–10 *Watznaueria barnesae* (Black)
9 L8, phase-cantrast light.
10 L8, cross-polarized light.
11–12 *Tetralithus aculeus* (Stradner)
11 L1, ardinary light.
12 L1, cross-polarized light.
13–14 *Tetralithus nitidus trifidus* (Stradner)
13 L8, ardinary light.
14 L8, cross-polarized light.
15 *Tetralithus nitidus nitidus* Martini
15 L7, cross-palarized light.
16 *Prediscosphaera cretacea* (Arkhangelsky)
16 L2, phase-contrast light.
17–18 *Lucianarhabdus cayeuxi* Deflandre
17 L8, cross-palarized light.
18 L8, phase-contrast light.

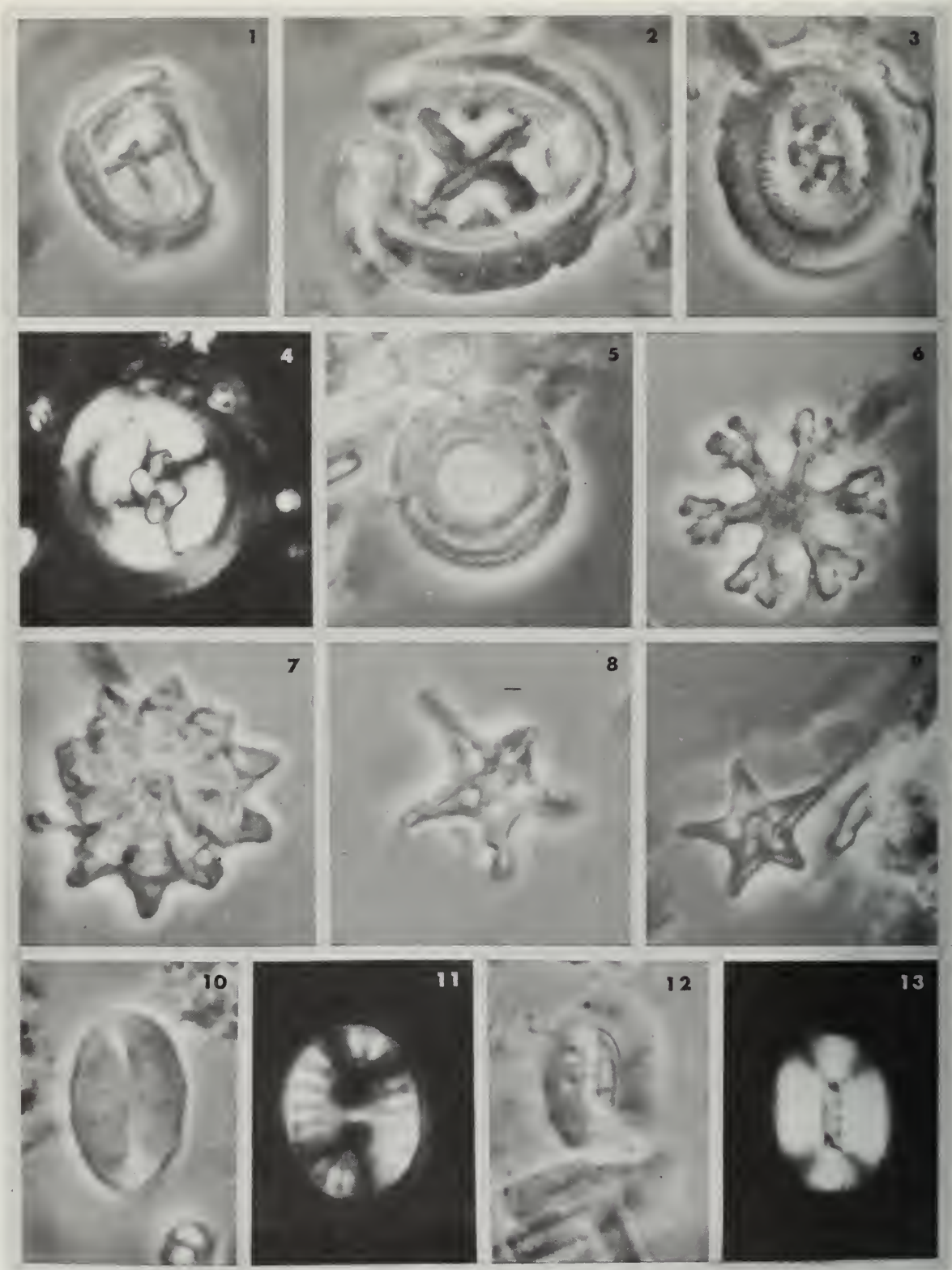
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Figure 3. Eocene Coccoliths ot San Diego, Califarnia (all magnifications X2500).

1 *Compylasphoero delo* (Bramlette and Sullivan)
1 L11, phase-cantrast light.
2 *Chiasmalithus grondis* (Bramlette ond Riedel)
2 L11, phase-cantrost light.
3–4 *Chiosmolithus stourian* (Bramlette and Sullivan)
3 L11, phase-contrast light.
4 L11, crass-palarized light.
5 *Cyclocaccolithus lusitanicus* (Black)
5 L11, phase-cantrast light.
6 *Discooster distinctus* Martini
6 L11, phase-contrast light.
7 *Discaaster elegans* Bromlette and Sullivan
7 L10, phase-cantrast light.
8–9 *Discooster subladoensis* Bramlette and Sullivon
8 L11, phase-cantrast light.
9 L11, phose-contrast light.
10 *Discalithina plana* (Bramlette ond Sullivan)
10 L11, phase-controst light.
11 *Discolithino pulchro* (Deflondre)
11 L12, cross-polarized light.
12–13 *Ellipsalithus* sp.
12 L11, phase-cantrast light.
13 L11, crass-palorized light.

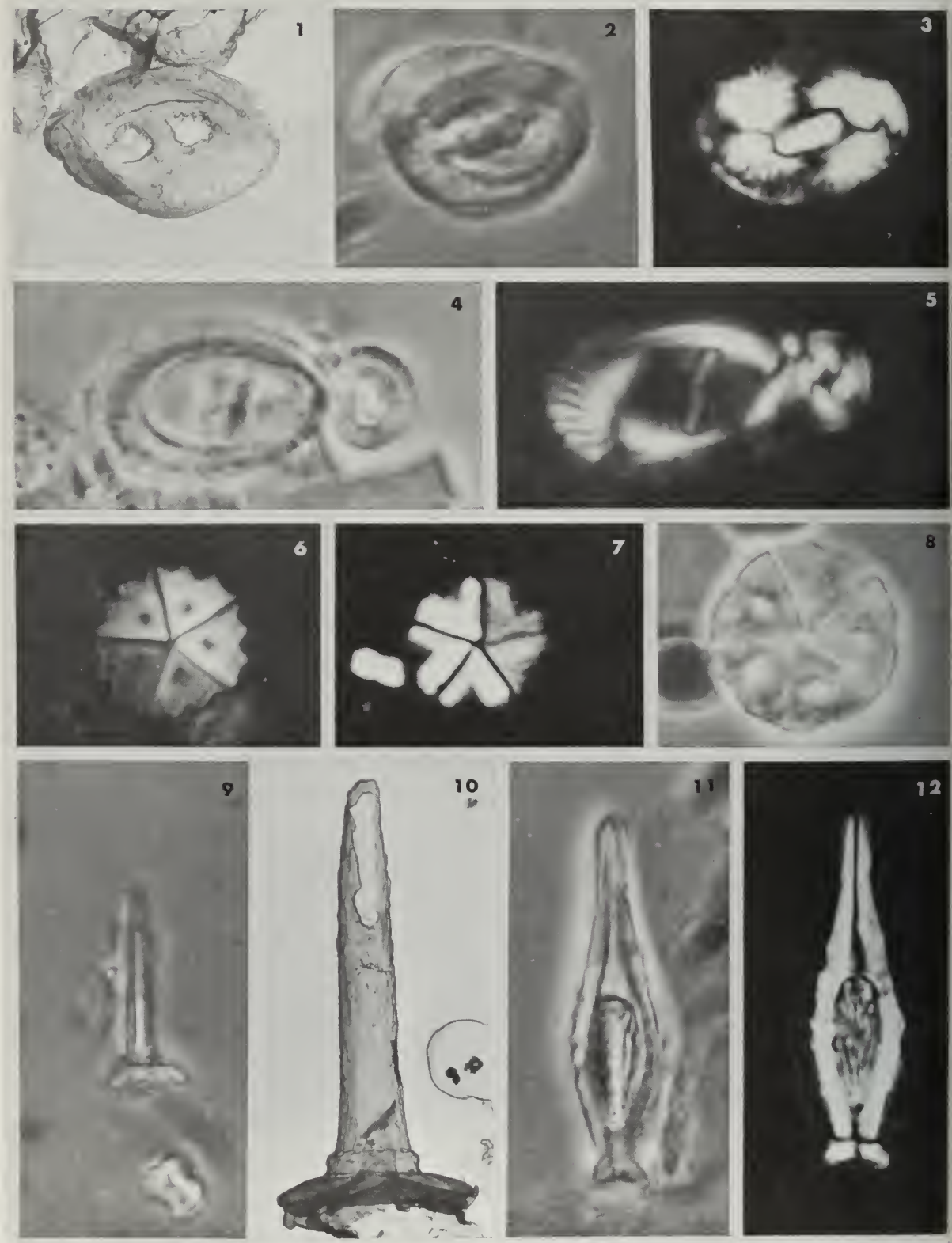
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Figure 4. Eocene Coccoliths ot San Diego, Colifornio (magnifications ×2500 except os noted).

1 *Helicopantosphaera* sp.
1 L11, Electron micrograph ×6000.

2–3 *Helicopontosphoero seminulum laphoto* (Bromlette ond Sullivon)
2 L11, phose-contrast light.
3 L11, cross-polarized light.

4–5 *Laphadolithus mochlophorus* Deflandre (ellipsoid ot left)
Caccolithus pseudagommotian Bouché (disc ot right)
4 L11, phose-controst light.
5 L11, cross-polorized light.

6 *Micronthotithus basquensis* Mortini
6 L12, cross-polorized light.

7 *Micronthotithus flos* Deflondre
7 L11, cross-polorized light.

8 *Micronthotithus parisiensis parisiensis* Bouché
8 L11, phose-contrast light.

9–10 *Rhabdasphoera crebra* (Deflondre)
9 L10, phose-controst light.
10 L11, electron micrograph ×7200.

11–12 *Rhobdosphoera inflota* Bramlette and Sullivon
11 L11, phose-controst light (air bubble within tube).
12 L11, cross-polorized light.

Table 2. Eocene Coccoliths at San Diego, California

Coccolith taxa	Sample localities					
	9	10	11	12	13	
Order Heliolithae **Deflandre**						
Campylosphaera dela **(Bramlette and Sullivan)**		X	X	X		
Chiasmolithus consuetus **(Bramlette and Sullivan)**			X			
C. grandis **(Bramlette and Riedel)**			X		X	
C. solitus **(Bramlette and Sullivan)**	X	X		X	X	
Coccolithus **sp. cf.** C. crassus **Bramlette and Sullivan**						X
C. eopelagicus **(Bramlette and Riedel)**		X			X	
C. pelagicus **(Wallich)**	X	X	X	X	X	
C. pseudogammation **Bouche**	X	X	X	X	X	X
C. staurion **Bramlette and Sullivan**			X			
Cyclococcolithus gammation **(Bramlette and Sullivan)**	X	X				
C. lusitanicus **(Black)**	X		X	X	X	X
Discolithina distincta **(Bramlette and Sullivan)**	X	X	X			
D. exilis **(Bramlette and Sullivan)**					X	
D. fimbriata **(Bramlette and Sullivan)**	X		X			
D. plana **(Bramlette and Sullivan)**		X	X			
D. pulchra **(Deflandre)**	X	X	X	X	X	
Ellipsolithus **sp.**			X			
Helicopontosphaera seminulum seminulum **(Bramlette and Sullivan)**	X	X			X	
H. seminulum lophota **(Bramlette and Sullivan)**	X	X	X		X	X
Lophodolithus mochlophorus **Deflandre**			X			
L. **sp. cf.** L. nascens **Bramlette and Sullivan**					X	
Reticulofenestra **sp. cf.** R. umbilica **(Levin)**	X		X	X	X	X
Rhabdosphaera crebra **(Deflandre)**		X	X			
R. inflata **Bramlette and Sullivan**	X		X			
R. morionum **(Deflandre)**			X			
R. scabrosa **(Deflandre)**			X			
R. tenuis **Bramlette and Sullivan**			X			
R. vitrea **(Deflandre)**			X			
Sphenolithus radians **Deflandre**		X	X		X	X
Order Ortholithae **Deflandre**						
Braarudosphaera bigelowi **(Gran and Braarud)**			X			
B. discula **Bramlette and Riedel**			X			
Discoaster barbadiensis **Tan**	X	X			X	
D. distinctus **Martini**		X	X		X	
D. elegans **Bramlette and Sullivan**		X	X			
D. nonaradiatus **Klumpp**		X	X			
D. septemradiatus **(Klumpp)**					X	
D. sublodoensis **Bramlette and Sullivan**		X	X			
Lanternithus minutus **Stradner**			X			
Micrantholithus attenuatus **Bramlette and Sullivan**			X			
M. basquensis **Martini**			X	X		
M. crenulatus **Bramlette and Sullivan**			X			
M. flos **Deflandre**			X			
M. parisiensis parisiensis **Bouche**			X	X		
M. vesper **Deflandre**			X			
Pemma rotundum **Klumpp**			X	X		
Zygrhablithus bijugatus **(Deflandre)**	X	X	X		X	

assemblage is indicative of late Campanian to Maestrichtian age (Bramlette and Martini, 1964; hardt, 1966; Gartner, 1968; Bukry, 1969). In it work on foraminifers from San Diego, Sliter 8) assigned a middle to late Campanian age to the of localities L1, L2 and L5 to L7 and an early trichtian age to the strata of localities L3, L4 L8.

EOCENE CORRELATION

ne material collected for this study from the Rose on Shale Member of the La Jolla Formation of na (1926) contains varied amounts of coccoliths related nannofossils (table 2). The richest samples ain a diverse flora that allows definite correlation the upper part of the lower middle Eocene *Dis-er sublodoensis* Concurrent-range Zone. The flora nis zone has previously been reported from the as Siltstone Member of the Kreyenhagen Forma-on Garza Creek near Oil City, California; from niddle Lutetian strata at Gibret, France; possibly the upper part of the Weches Formation in east Texas by Bramlette and Sullivan (1961); the Lutetian strata of the Paris Basin in France ouché (1962); from the upper part of the Anita of Kelley (1943) in Santa Barbara County, by an (1965), and from the upper part of the Lodo nation in Kern County, California. Examination pe material from the lower middle Eocene *Hantkenina aragonensis* Range Zone of foraminifers in Trinidad also shows a coccolith assemblage correlative with the Rose Canyon Shale Member flora. The occurrence at La Jolla of such coccolith species as *Discoaster sublodoensis* Bramlette and Sullivan, *Discolithina exilis* (Bramlette and Sullivan), *D. fimbriata* (Bramlette and Sullivan), *Lophodolithus mochlophorus* Deflandre, and *Rhabdosphaera inflata* Bramlette and Sullivan indicates close correlation of the Rose Canyon Shale with Bramlette and Sullivan's unit 5, which has recently been considered part of the *Discoaster sublodoensis* Concurrent-range Zone of Hay and others (1967).

CONCLUSION

Coccoliths provide a valuable method, independent of foraminifers, for long-range correlation of marine rock sequences. The cosmopolitan nature of entire coccolith assemblages is well demonstrated in the San Diego collections. All the Cretaceous taxa of coccoliths recorded at San Diego and essentially all the Eocene taxa have previously been recorded from Europe. Application of coccoliths to the stratigraphy of the marine strata of western North America has only recently begun, but valuable results obtained thus far (Bramlette and Sullivan, 1961; Bramlette and Wilcoxon, 1967; Garrison, 1967; Garrison and Bailey, 1967; Lipps, 1967, 1968; Sullivan, 1964, 1965) certainly support the expansion of such efforts.

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RATIGRAPHY AND PETROLOGY F THE LOST BURRO FORMATION, ANAMINT RANGE, CALIFORNIA*

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ABSTRACT

he Lost Burro Formation (Middle and Upper Devonian), ut 2000 feet thick, extends from the Inyo Mountains he Nopah Range. A regional change from a lower eozoic dolomitic sequence to upper Paleozoic limestone urs within the unit.

n the vicinity of the type locality, the Panamint Range, formation consists mainly of gray, thick-bedded, gener- poorly fossiliferous carbonates, and comprises five s, in ascending order: (1) Lippincott Member, 250 feet quartzose and cherty dolomite; (2) 500 feet of chiefly -insoluble, saccharoidal dolomite including the *Stringo-chalus* zone; (3) 600+ feet of fine-grained limestone d dolomite, including stromatoporoid biostromes, and e sandstone; (4) 460 feet of predominantly very fine- ined limestone; (5) Quartz Spring Sandstone Member, eet of thinner bedded cherty limestone and calcareous, omitic sandstone containing *Cyrtospirifer*. The contacts h the underlying Hidden Valley Dolomite and the over- g Tin Mountain Limestone are sharp but are considered entially conformable.

errigeneous material is chiefly quartz, microcline, and uscovite." The median insoluble content is about two rcent. There is no correlation between insoluble residue dolomite content. Petrographically, the unit is divided nine microfacies. The dolomites are generally equi- nular, xenotopic to hypidiotopic, and are zoned with t, microcrystalline inclusions; the grain size ranges from to medium sand. Limestones, with a micritic to silt-sized undmoss, are inequigranular, xenotopic, and contain ids, calcispheres, and some fossil fragments. In mixed bonates, the idiotopic dolomite contains calcite inclu- s; a replacement origin for dolomite is indicated. Dolo- ation was interrupted by silicification. The environment leposition was shelf-like, the limestone probably repre- ing lower energy, farther offshore deposits than the omite.

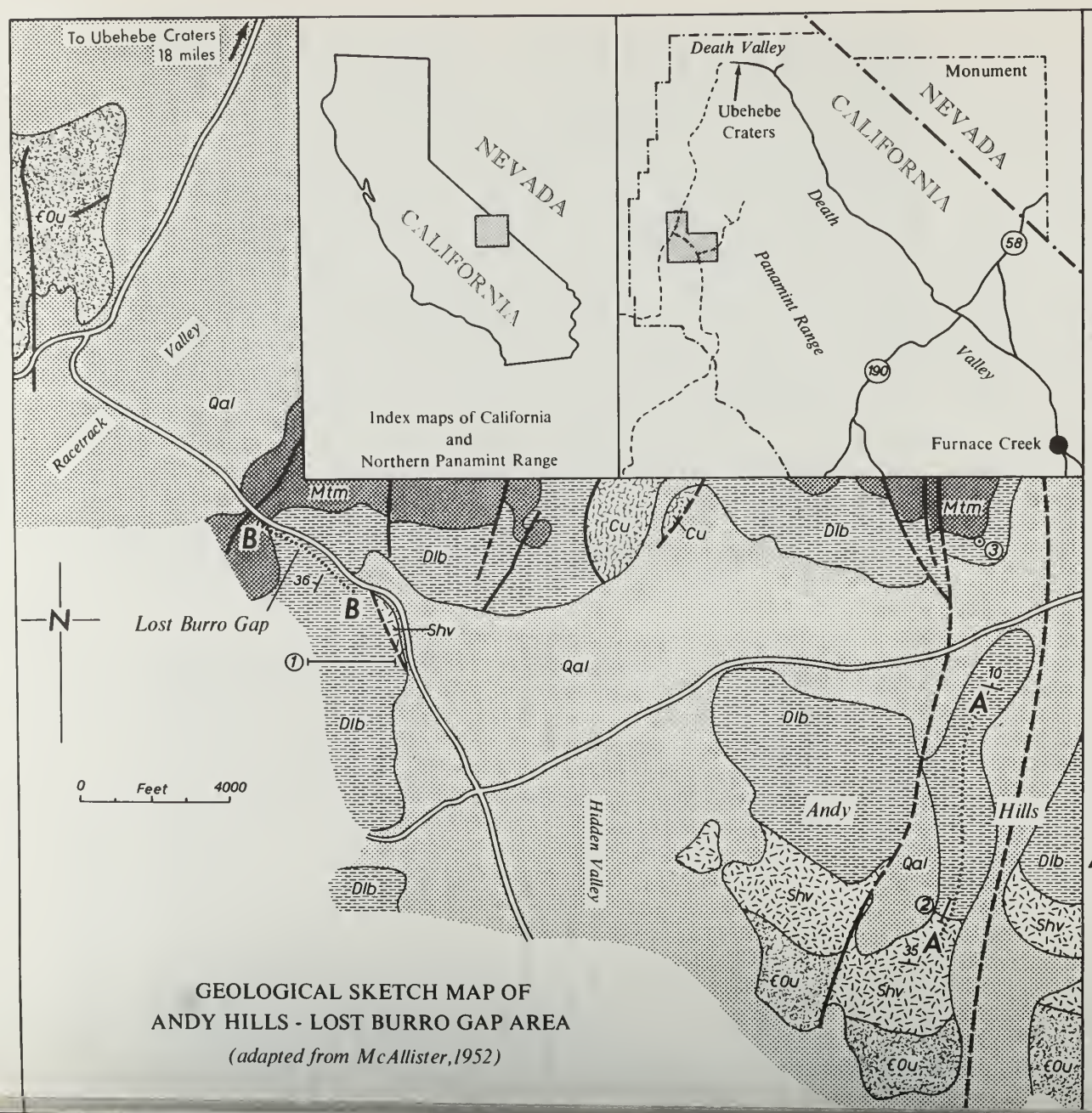
nuscript submitted for publication April 1968.

INTRODUCTION

Objectives

The Lost Burro Formation, named by McAllister (1952, p. 18), is a predominantly carbonate sequence of Middle and Late Devonian age, about 2,000 feet thick. It extends from the southern Inyo Mountains of California eastward to the Nopah Range near the Nevada line. Within this unit occurs the regional change from Ordovician through Middle Devonian dolomites to Upper Devonian and later Paleozoic limestones. Previous descriptions of the Lost Burro have been brief, presented in conjunction with mapping projects or reports on mining districts. Consequently, there has been no stratigraphic synthesis and there is a notable lack of any detailed petrologic treatment of the unit. For these reasons, and also because the limestone-dolomite relations provide an interesting background for a study of dolomitization, the Lost Burro is being examined along its outcrop belt.

Stratigraphic study, in large part of a reconnaissance nature, has been undertaken by us on the unit, or its equivalents, from the Panamint Range on the west to the Nopah Range and vicinity on the east. At the type locality, just south of Lost Burro Gap in the Panamint Range (fig. 1), the section is not ideal, because of structural complications. However, observations made elsewhere across the outcrop belt indicate that the type locality shows well the dominant characteristics of the unit. In view of this, it becomes important to redefine to some extent the stratigraphy in the type area. The primary purpose of the paper is to present the details of the petrology of a composite reference section in the vicinity of the type locality. Later work will treat the stratigraphy and petrology over the entire area of occurrence.



GEOLOGICAL SKETCH MAP OF
ANDY HILLS - LOST BURRO GAP AREA
(adapted from McAllister, 1952)

Explanation

- Qal — Quaternary Alluvium
- Cu — Carboniferous Undivided strata
- Mtm — Lower Mississippian Tin Mountain Limestone
- Dlb — Middle-Upper Devonian Lost Burro Formation
- Shv — Silurian-Lower Devonian Hidden Valley Dolomite
- €Ou — Cambrian-Ordovician Undivided strata
- Contact
- Dip and strike of beds
- Faults, dashed where inferred
- A ····· A' Line of section traverse
- ① Type locality, Lost Burro Formation
- ② Reference section, Lippincott Member
- ③ Type locality, Quartz Spring Sandstone Member

Methods and Procedures

Samples for petrologic study (149, including six m underlying and overlying units) were collected stratigraphic intervals usually ranging from 10 to 20 t, along the two traverses (A-A′; B-B′) shown in ure 1. Some collections were made at closer inter- ls because of rapid vertical changes in lithology.

Laboratory analyses were conducted along several es. Quantitative insoluble residue determinations re made by three 12-hour treatments with 10% Cl, a slight variation of the procedure of Ellingboe d Wilson (1964). This procedure and the choice of d strength is a compromise between minimal effect clay minerals and practicality in carbonate digestion ie. Crushed rock samples, as well as the dried resi- es, were analyzed by X-ray diffraction using a ilips X-ray Diffractometer. In the residues, terrige- us components of low-insoluble rocks could be ermined despite their rarity and consequent absence the X-ray scans of the original rock samples.

Densities were determined using a Beckman Air mparison Pycnometer (#930). Eighteen replicate asurements of a sample of dolomite gave a standard iation of 0.0027 units. Calcite-dolomite ratios could determined by this procedure, the difference be- een calcite and dolomite (about 0.15 gm/cc) being ficiently large, when compared to the precision of instrument, to permit detection of small differences the proportion of the carbonates (Zenger, 1968).

An electron probe microanalyzer (Philips Electronic truments AMR/3) was used to determine calcium d magnesium distribution in selected samples.

Thin sections were stained with acidic solutions of zarin Red S (positive for calcite) and potassium ricyanide (positive for ferrous iron), and polished k slabs with a basic solution of Alizarin Red S olomite positive).

ACKNOWLEDGMENTS

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PREVIOUS WORK

McAllister (1952, p. 18–20) defined and described the Lost Burro Formation in his report on the geology of the Quartz Spring area. The type locality was established on the western side of Lost Burro Gap (fig. 1), near its southern entrance. In the measured section (inferred to be the type section) at the type locality, he divided the "1525" feet of the formation into five units, in ascending order as follows: (1) 155 feet of sandy, cherty dolomite and quartzite conformably above the Hidden Valley Dolomite (Silurian and Lower Devonian); (2) 470 feet of dark- and light-gray dolomite; (3) 530 feet of dark-gray dolomite with white forms resembling spaghetti [*Amphipora*] interbedded with light- and dark-gray limestone and dolomite with stromatoporoids; (4) 335 feet of light-gray and medium-gray dolomite; (5) 35 feet of light-gray, sandy dolomite and quartzite with *Cyrtospirifer* overlain conformably by the Tin Mountain Limestone (Mississippian). Later (1955, p. 12), McAllister applied the name "Lippincott" to the lower cherty and quartzitic member that is locally lead-bearing to the southwest. Langenheim and Tischler (1960, p. 92) designated the upper quartzite and interbedded dolomitic sandstone (equivalent to McAllister's unit 5) as the Quartz Spring Sandstone Member. Youngquist and Heinrich (1966) discovered fragmentary conodonts in this unit.

Reports on the Lost Burro Formation, or its equivalents elsewhere within the area under consideration, include that by Merriam (1963, p. 14–17) in the southern Inyo Mountains, where he reported 1500 to 1600 feet, mostly limestone or marble. Hall and Mackevett (1958, p. 8), in the Darwin quadrangle, estimated between 1700 and 2400 feet of dolomite, sandy limestone, quartzite, shale, chert, and marble in the formation. Hall and Stephens (1963, p. 14) reported more than 1500 feet of Lost Burro at Panamint Butte, where the lower part is predominantly dolomite and the upper part mainly limestone with some dolomite. More than 2000 feet of Lost Burro is estimated for the Funeral Mountains east of Death Valley, where it includes a lower dolomite and an upper limestone. A similar section more than 1700 feet thick occurs in the Nopah Range, although this sequence has been assigned by Hazzard (1937, 1954) to Hewett's (1931) Sultan Limestone (of the Goodsprings, Nevada, area). Hamill (1966, p. 36–41) considered the lower 870 feet of dolomite of the equivalent section north of Pahrump, Nevada, as the Nevada Formation, and he assigned the upper 1700 feet, mostly limestone, to the Devils Gate Limestone. Although similar stratigraphy may continue farther east in Nevada, the writers have not investigated this possibility in detail. Consequently, at present, the discussion of the Lost Burro Formation is restricted to the area mentioned.

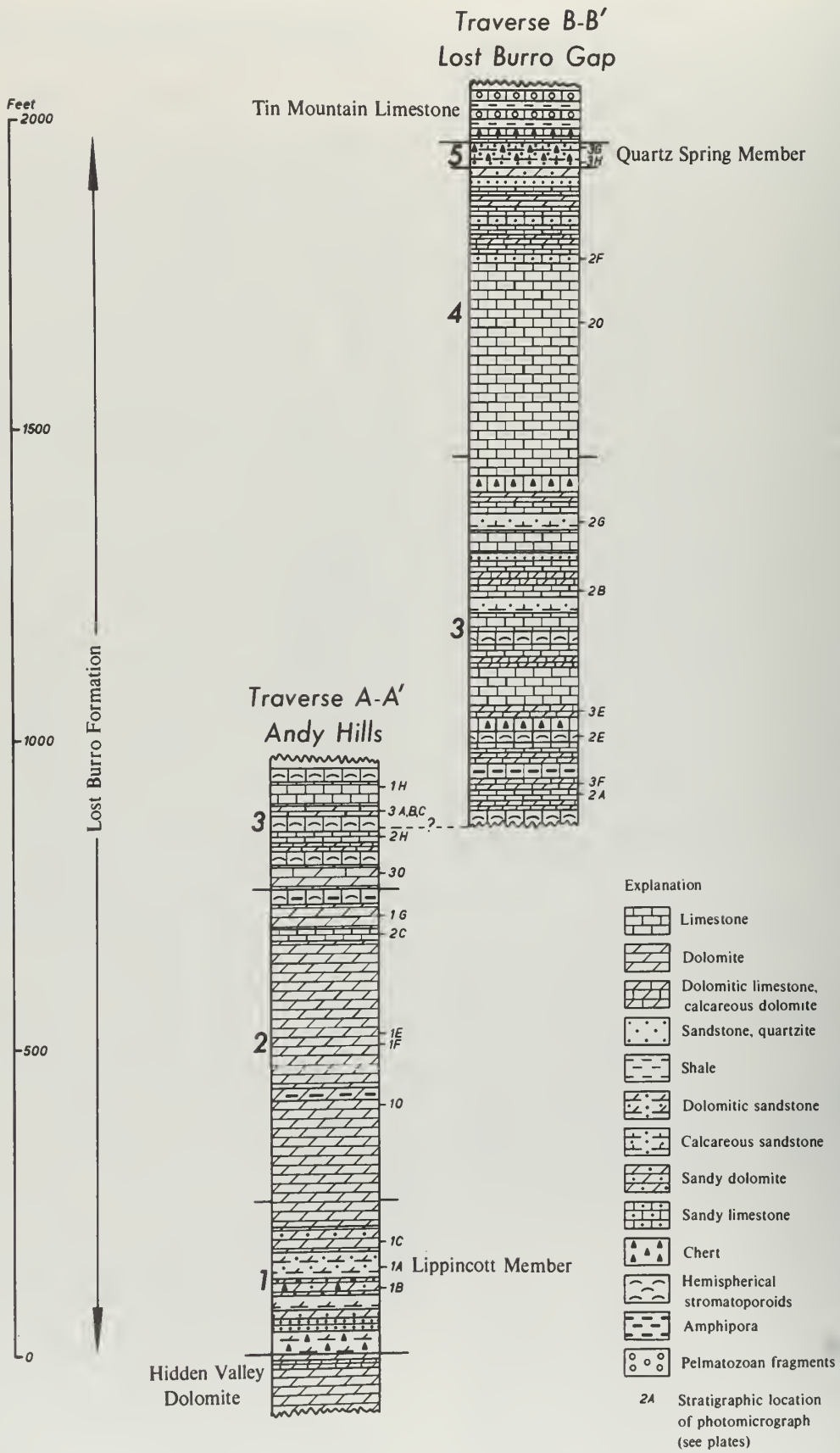


Figure 2. Columnar Section. Composite reference section of Lost Burro Formation seen in and neor type locality.

THE TYPE LOCALITY AND VICINITY

General

connaissance work on the Lost Burro Formation
ie southwestern Basin and Range Province has
led the widespread nature of sedimentary char-
istics found in the vicinity of the type locality.
ppears possible that the Lost Burro, as herein
ibed in the Lost Burro Gap area, can be extended
er eastward (i.e., into the Nopah region) than
previously thought. In fact, Upper Devonian units
alent to the upper, or limestone portion, show
rkably persistent characteristics as far east as
rn Nevada and as far north as Alberta, Canada.

vo sections were studied and collections made
g traverses A-A′ and B-B′ (fig. 1). Traverse A-A′,
e north-dipping section in the Andy Hills, exposes
ower part of the Lost Burro Formation and its
act with the underlying Hidden Valley Dolomite
out 5500 feet in elevation; traverse B-B′, in the
west-dipping section along the road through Lost
o Gap, exposes continuously the middle and
r parts of the unit and the overlying Tin Moun-
Limestone (contact at altitude of about 4520 feet).
uppermost beds of A-A′ cannot be correlated
ly with the lower parts of B-B′ (fig. 2), but the
ness of the formation appears to exceed 1900 feet.
figure is considerably higher than that given by
llister (1952, p. 18) for the inferred type section
diately southeast of B-B′ (fig. 1), although he re-
d a thickness of 2245 feet for a neighboring
on (1952, p. 19). The entire Lost Burro Formation
not be exposed at McAllister's section because of
obable fault contact between that unit and the
rlying Hidden Valley. Because we feel this type
on is not adequate in itself, we propose as a refer-
section the composite one along the two traverses
ibed. It should be pointed out that the lower
on of our composite reference section, namely
in the Andy Hills (figs. 1 and 2), is coincidental
McAllister's measured section (1952, p. 19). In a
report McAllister (1955, p. 12), he described this
on again, as a reference section for the Lippincott
ber. Furthermore, the other segment of our com-
e reference (section B-B′) is actually in the type
ity designated by McAllister (1952, p. 18) but is
Lost Burro Gap, just north of his measured sec-
(see fig. 1).

Stratigraphy

e Lost Burro Formation at the composite refer-
section is divisible into five lithic units (fig. 2),
ugh the divisions differ somewhat from those of
llister (1952, p. 18). This subdivision emphasizes
portance of limestone in the upper three units.
t in the thin-bedded Quartz Spring Sandstone
er, medium and thick bedding are character-
Contacts between the units are considered con-
ble. Both limestones and dolomites are severely
red, the fractures being filled with secondary calcite and dolomite. Many beds emitted a fetid odor when sampled.

Unit 1, or Lippincott Member, consists of 250 feet of gray, quartzose, fine to coarsely crystalline, occasionally laminated dolomite, with beds and lenses of quartzite (fig. 3), commonly cross-bedded, and chert bodies being particularly abundant in the lower part. The conformable contact with the underlying Hidden Valley Formation is set at the lowest abundant quartzites at the base of a relatively steep scarp. Although the Hidden Valley is almost exclusively dolomitic, calcareous beds occur just above the "*Spirifer*" *kobehana* zone and immediately below the Lippincott quartzites.

Unit 2 consists of 500 feet of primarily very finely crystalline to coarsely crystalline, saccharoidal, light-gray to dark-gray dolomite. A few limestone beds occur in the uppermost part. Fossils are generally rare, the commonest being poorly preserved specimens of the digitate stromatoporoid *Amphipora,* usually in biostromes. One of these in the uppermost part may represent the *Stringocephalus* zone although none of these brachiopods was found. However, *Stringocephalus(?)* has been found by McAllister (written communication, 1966) about 700 feet above the base of the formation on the ridge parallel to and east of A-A′. The *Stringocephalus* zone is typically within the uppermost part of the lower, dolomitic portion of the Lost Burro in the southwestern Basin and Range region. Other fossils include brachiopod and tetracoral fragments, commonly silicified, with hemispherical stromatoporoids appearing near the top of the unit. Rare quartzite bodies and some chert occur in the upper part of the unit.

Unit 3 is more than 600 feet thick. Its base is drawn at the change from predominantly dolomite to predominantly limestone. The lower part is well exposed south of structural complications along A-A′, whereas the upper part, and perhaps most of the lower part, are exposed along Lost Burro Gap (figs. 1 and 2). Alternating light and dark bands are characteristic and a variety of lithologies include dark-gray, medium-crystalline, biostromal limestone with silicified stromatoporoids and some chert (fig. 4); dark-gray, fine-crystalline, saccharoidal dolomite in places weathering to a conspicuous light gray, and in places boudinaged; medium-gray, aphanitic limestone; mixed carbonates, particularly calcareous mottles in a dolomite matrix and also calcareous stromatoporoids (clathyrodictyids and *Amphipora*) and cladoporoids(?) in a more dolomitic matrix; and minor brownish-weathering, calcareous quartz sandstones. Fossils other than stromatoporoids are rare, two fragments of *Atrypa*(?) being found in the lower part. There are a few stratigraphic trends within the unit such as a decrease in importance of coelenterates upward and the main occurrence of sandy beds in the upper part.

The lower 400 feet of unit 4, totaling about 460 feet, is generally unfossiliferous, very fine-grained, medium-gray limestone similar to that present in unit 3, especially in the upper part. The upper 60 feet of

Figure 3. Dolomitic Sondstone ond Quartzite. The view is of the lower port of the Lippincott Member, traverse A-A' in Andy H s. quartzite is dork-weathering.

unit 4 includes also fine-grained dolomite and calcareous dolomite beds made prominent by their grayish-orange weathering, mixed carbonates—interlaminated and mottled, and medium-grained calcareous sandstones and quartzites in the uppermost part. The upper contact with the Quartz Spring Sandstone Member is marked by small-scale channelling and filling by sandstone in a mixed carbonate bed. Shell debris occurs above and below the contact and it is thought to be conformable although Langenheim and Tischler (1960, p. 99) considered it as paraconformable at the nearby type section (their fig. 1 and p. 92; fig. 1 of this report) of the Quartz Spring Sandstone Member and the overlying Tin Mountain Limestone.

The 30-foot Quartz Spring Sandstone Member is conspicuous at the top of the Lost Burro Formation by virtue of its dark, yellowish-brown weathering (fig. 5). The dominant lithology is gray, laminated to thin-bedded, fine- to medium-grained, in part calcareout sandstone, although X-ray analysis shows the presence of small amounts of dolomite. Chert, as elongate pods parallel with the bedding or as nearly continuous beds, is most common low in the unit, which becomes coarser upward. Spiriferid brachiopods, including *Tylothyris* and *Cyrtospirifer* are abundant in some layers. Youngquist and Heinrich (1966, p. 975) reported poorly preserved specimens of the co genera *Hibbardella*, *Ligonodina*, *Palmatolepi Polygnathus* from this unit.

The lowermost part of the overlying Tin Mo Limestone is less erosion resistant than the upp of the Lost Burro Formation, is thin- to m bedded, darker weathering, finer grained an sandy. Chert nodules occur in the lowest part Tin Mountain and pelmatozoan fragments are mon throughout, although it should be noted tha pelmatozoan material was also observed in the Spring Sandstone Member. Pale reddish-purple between the gray limestone beds are diagnost intercalated gray shales begin about 20 feet abo base of the Tin Mountain. Abundant fossils inc crinoids, syringoporid and auloporid corals, a athyridacean brachiopod were found in a zone 35 feet above the base. The Lost Burro-Tin Mo contact is marked by what appears to be limy of small depressions in the Los Burro surface sharp, irregular contact, as well as the chang calcareous sandstone to limestone, may repre small break, but we consider the sequence to be tically conformable. Faunal evidence present Langenheim and Tischler (1960, p. 102–103) su a latest Devonian age for the Quartz Spring San

Figure 4. Silicified Stromatoporoids. The fossils are in limestone, unit 3.

er and an Early Mississippian age for the Tin ain Limestone. These data seem to indicate that positional break occurred between the units it minor one.

Petrology

hoped that this study will provide a description 'petrologic type section"; it appears that the raphic characteristics, as well as the stratigraphic, extend over a large area. The petrology is discussed under the various methods of analysis (see also "Introduction" for statements regarding methods and procedures).

QUANTITATIVE INSOLUBLE RESIDUE ANALYSIS

Of 127 carbonate samples (less than 50% terrigenous matter) from the Los Burro, the mean insoluble residue is 4.59%, the median being 1.68%. If all 143

Figure 5. Upper Lost Burro Formation in Lost Burro Gap. The view is to the northwest along traverse B-B'. TM = Tin Mountain, 5 = unit 5 (Quartz Spring Sandstone Member), 4 = unit 4.

Table 1. Quantitative Insoluble Residue and Density Determinations

Unit	No. of Samples	Insoluble Residue Mean (%)	Insoluble Residue Median (%)	Density (gm/cc)
Lowermost Tin Mountain Limestone	3	6.41	6.09	2.719
Lost Burro Formation				
Unit 5 (Quartz Spring Sandstone Member)	8	64.88	64.70	2.697
Unit 4	33	7.81	1.35	2.728
Unit 3	67	8.21	1.89	2.749
Unit 2	24	1.42	0.88	2.850
Unit 1 (Lippincott Member)	11	23.02	17.58	2.810
Uppermost Hidden Valley Dolomite	3	9.20	9.53	2.802

samples are included, the mean becomes 11.81% and the median 2.09%. Sampling was not intended to be random; homogenous units, such as the main part of unit 4, were sampled less closely than the thinner, more variable, and more highly insoluble Quartz Spring Sandstone Member. The median provides a better representation of the average insoluble content. Sandstone beds are rare, considering the whole formation, but their relative abundance in the Lippincott and Quartz Spring Members affects the mean more drastically than the median. Table 1 shows the quantitative results for the various units.

QUALITATIVE X-RAY DIFFRACTION ANALYSIS

Briquettes of "whole rock" samples were scanned between 20° and 40° 2θ, whereas samples of the insoluble residues were scanned down to 5° 2θ in order to include low-angle reflections from the large basal d-spacings of any clay minerals present. Figure 6A shows representative scans for typical rock samples of each unit; figure 6B comprises X-ray scans of the insoluble residues of the corresponding samples of 6A. These show that the major terrigenous material is quartz including chert), microcline (which is distinguishable from other feldspars by its main reflection at $2\theta = 27.4°$), and "muscovite." The conditional use of the latter is owing to the difficulty in distinguishing illite from muscovite. According to Brown (1955, p. 663), Grim (1953, p. 94), and Güven and Kerr (1966, p. 1062), it would appear that muscovite-type layers might be distinguished from illite on the basis of the relatively high and low intensities of the 3.3Å and 5Å spacings, respectively, of muscovite. A relatively strong peak at about $2\theta = 26.8°$ is commonly detectable on the flank of the major quartz reflection. Although muscovite may be suggested by relative peak heights, the conditional use of "muscovite" includes any illite present.

Other residues roughly in order of decreasing abundance are kaolinite, montmorillonite, and, in one sample, orthoclase(?). A few stratigraphic generaliz can be made. Quartz, chert, and microcline a dominant terrigenous constituents in the Lipp and Quartz Spring Sandstone Members, clay m being extremely minor, in contrast with thei spicuous presence in the uppermost Hidden Dolomite and lowermost Tin Mountain Lime Quartz and "muscovite" are the major terri components of units 2, 3, and 4, kaolinite and morillonite being present but relatively minor. morillonite is practically restricted to unit 3 w microcline is least significant within the middle unit.

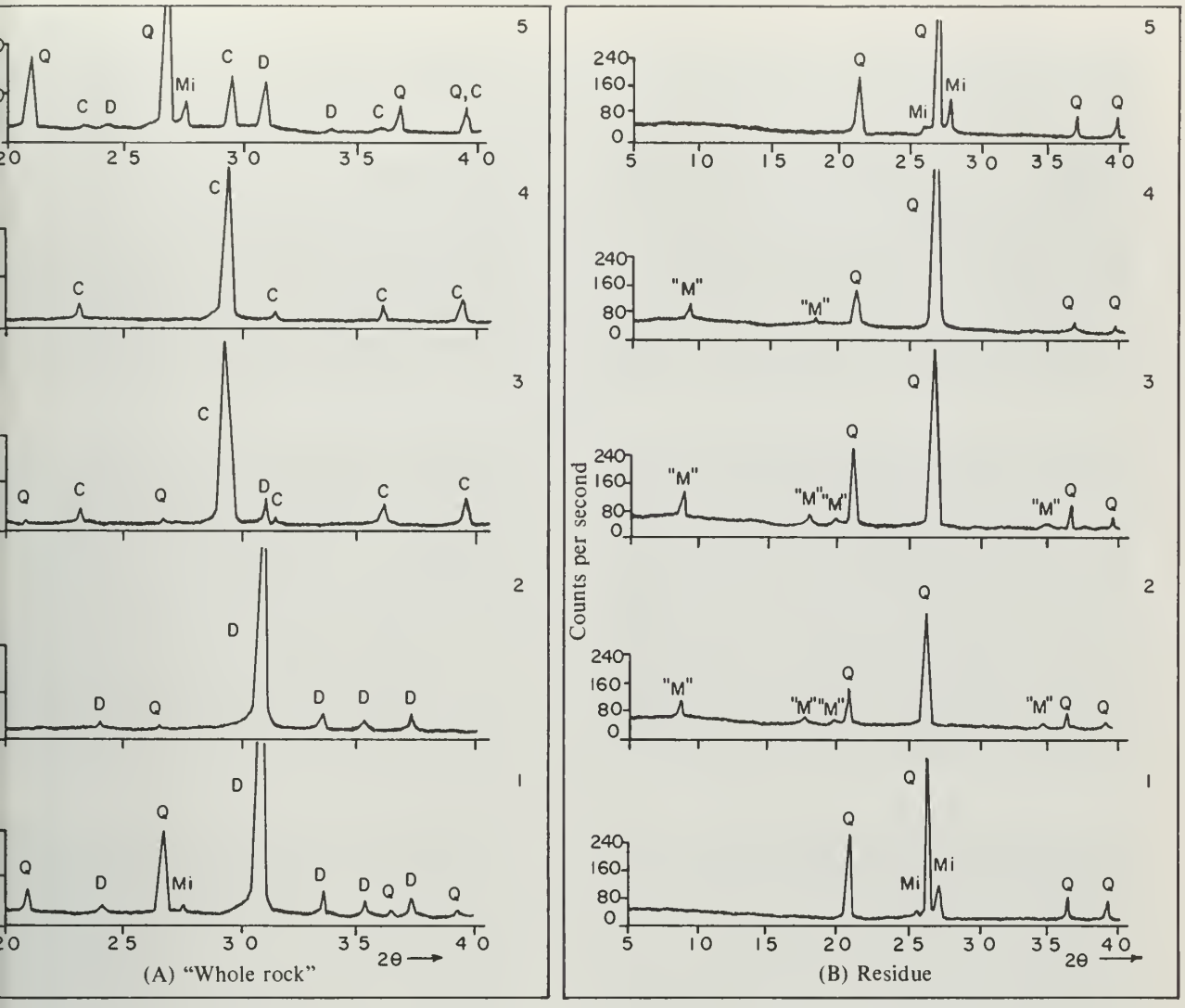
AIR PYCNOMETER DETERMINATION OF DENSITY

Density values (table 1) reflect the relative i tance of the three main variables in the rocks: 2.65; calcite, 2.72; and dolomite, 2.86. Unit 2 h highest average as it consists of low-insoluble dol Although the carbonate content of the Lipp Member is also dolomite, the presence of quart chert reduces the specific gravity. Calcite-do ratios can also be determined with the air pycno (Zenger, 1968). The method compares favorably X-ray diffraction techniques and in this particula avoids the minor effect of small reflections of cline at approximately the positions of the maj flections of calcite and dolomite. A test to dete any relation between insoluble content and do percent (as determined with the air pycnomete sulted in a correlation coefficient of 0.0530, shov lack of significant correlation between these var

THIN SECTION PETROLOGY

General

The exact origin of carbonate material, esp the finer grained portion, cannot always be mined. The use of such terms as calcisiltite, dolo and calcilutite were originally intended for the de



6. X-ray Diffraction Scans of Samples ond Residues. A: "whale rack" somples; B: corresponding residues. Numbers 1 ta 5 refer ta stratigraphic units.

clastic carbonates although subsequently they een used more liberally. The textures of the urro suite are those of crystallization which esult from precipitation, neomorphism (i.e., "re-zation"), or metasomatism. Grade scales for xhibiting textures and fabrics of crystallization een proposed by Folk (1959, p. 16), DeFord and most recently by Friedman (1965, p. 653). n's scheme, based primarily on the metric sys-ummarized below:

on-sized: 0.001 to 0.010 millimeters (0 to 10 crons)

nicron-sized: 0.01 to 0.10 millimeters (10 to 100 crons)

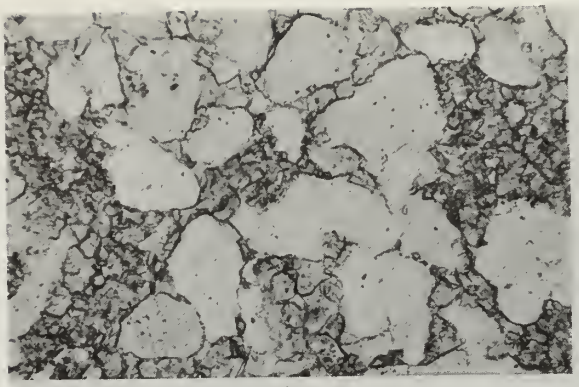
micron-sized: 0.10 to 1.00 millimeters (100 to 0 microns)

neter-sized: 1.00 to 10 millimeters

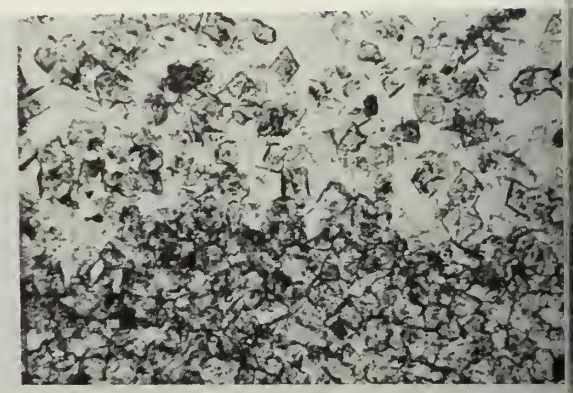
meter-sized: 10 to 100 millimeters

As Friedman subdivided the centimicron-sized range into fine crystalline (100–250 microns), medium crystalline (250 to 500 microns), and coarse crystalline (500 to 1000 microns), corresponding subdivisions are used in this report for the decimicron-sized range. Folk's (1961, p. 24) clastic grain size scale is followed.

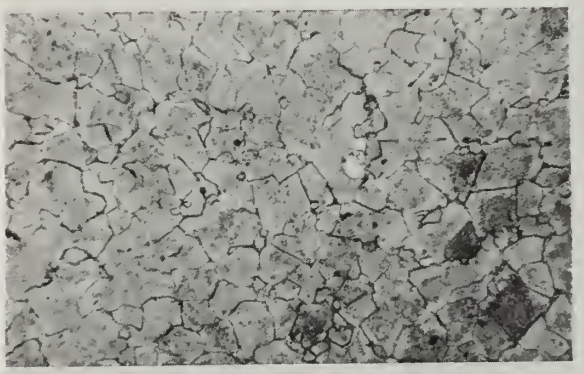
Friedman's (1965) terminology of crystallization textures and fabrics will be used with but slight modification. Friedman (1965, p. 648) proposed "xenotopic" for fabrics in which the majority of the constituent crystals are anhedral, "hypidiotopic" for fabrics in which the majority of crystals are subhedral, and "idiotopic" for those fabrics in which the majority are euhedral. As used by Friedman, the terms anhedral, subhedral, and euhedral refer to the degree of development of crystal *faces*. He did point out, however (p. 653), that a planar intercrystalline boundary between two crystals cannot represent a face of both crystals and is either a crystal face of one or a compromise boundary between the two. Furthermore,



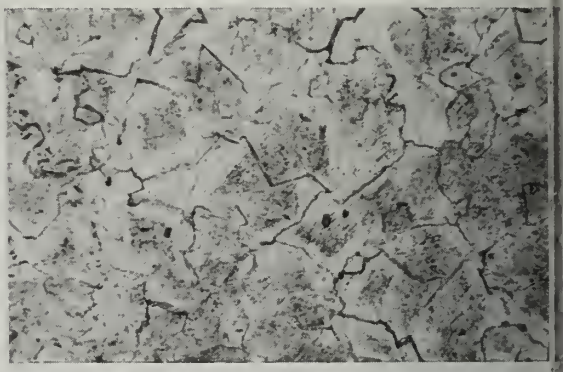
A



B

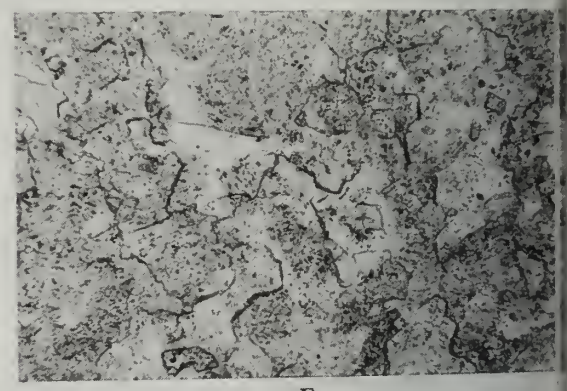


C



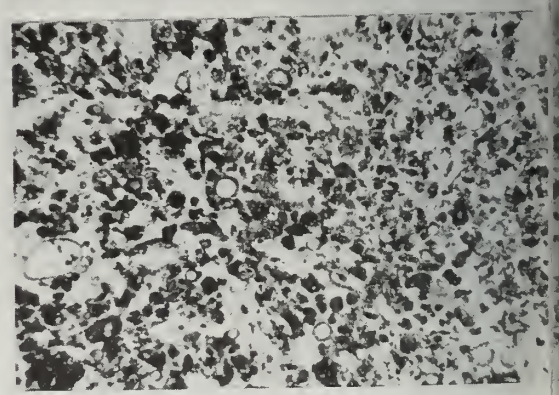
D

E



F

G



H

Plate 1. Photomicrographs.

oll photomicrogrophs ×20, length of short dimension = 2.8 mm; on oll photomicrogrophs ×80, length of short dimension = 0.7 mm.

ofocies A; xenotapic dolomite carroding quartz; ordinary , ×80; unit 1, Lippincott Member.

A

Microfacies A; xenatopic dolamite below grading upward into lamination of dalomitic quortzite ond chert, the dolomite becoming idiotopic; plone polarized light ×80; unit 1, Lippincott Member.

B

diotopic, centimicron-sized dolomite of microfocies B; note r quortz grains and "dusty" inclusions in places in rhombic ied areo bordered by "rim cement"; ordinary light, ×20; 1, Lippincott Member.

C

Shadowy, rhombic "zoning" in dolomite of microfocies C ond xenotopic to hypidiotopic fabric; ordinory light, × 80; unit 2.

D

topic, equigronulor dolomite, microfacies C; ordinory light,); unit 2.

E

"Dusty" zones (relic peloids ?) extending ocross dolomite grain baundaries; poikilotopic dolomite of microfocies D; plone polorized light, ×80; unit 2.

F

nated dolomite of microfocies C ond D; note microstylolites zone of hemotite groins in upper, coorser lominotian; ary light, ×20; unit 2.

G

Field of peloidol limestone, microfocies E; note calcispheres; plone polorized light, ×20; unit 3.

H

the only definitive method of determining whether or not a plane intercrystalline boundary is a crystal face is by the use of the universal stage as described by Bathurst (1964, p. 364–365). This procedure becomes impractical when analyzing large numbers of thin sections, and a descriptive scheme to be used with a less rigorous visual inspection of crystal boundaries is valuable. We have adopted Friedman's classification with the modification that the concept of "plane intercrystalline boundaries" be substituted for "crystal faces"; in this fashion, all straight boundaries are included whether or not they are true crystal faces.

Microfacies

Nine microfacies have been recognized within the Lost Burro. A brief description and notes on their occurrence with respect to the stratigraphic units is presented below (see also table 2). The stratigraphic positions of the photomicrographs (pls. 1–3) are indicated on the columnar section (fig. 2).

A. Quartzose dolomite and dolomitic sandstone. Equigranular, xenotopic to hypidiotopic, "dusty," decimicron-sized dolomite contains severely corroded, angular, coarse silt to medium-grained, predominantly very fine sand (pl. 1A). Dolomite is idiotopic against secondary silica and within chert (pl. 1B). This microfacies is restricted to unit 1 (Lippincott Member).

B. Coarse dolomite. Centimicron-sized (fine to coarse crystalline), hypidiotopic, predominantly equigranular dolomite commonly contains "dusty" inclusions occasionally as rhomb-shaped centers with clear borders (pl. 1C). Minor quartz and microcline (less than 5 percent) occur in the very fine sand range. Such grains are very corroded and in places are enclosed within large dolomite grains. Coarser, clearer spar in void fillings (veinlets or more equidimensional pockets) is generally minor but constitutes up to 50 percent of some specimens. This microfacies occurs in units 1 and 2.

C. Fine dolomite. Similar in some respects to B, this dolomite is decimicron-sized (coarse crystalline) and commonly more xenotopic (pl. 1D, E). Electron probe microanalysis indicates that the "dust" constituting the rhomb-shaped areas within the grains (pl. 1D) is silica-rich relative to the clear borders, suggesting the possibility that the tiny inclusions are clay particles. Some "dusty" areas overlap grain boundaries (pl. 1F). Coarser spar fills fractures and voids, some of which represent fossil fragments. Other pockets of coarser, clearer dolomite appear as "healed" (partly recrystallized) void fillings giving the appearance of a "micro" pseudobreccia. Some specimens show weak to strong alternate laminations of centimicron-sized and decimicron-sized grains, the latter being darker (pl. 1G). The microfacies is present in units 2 and 3.

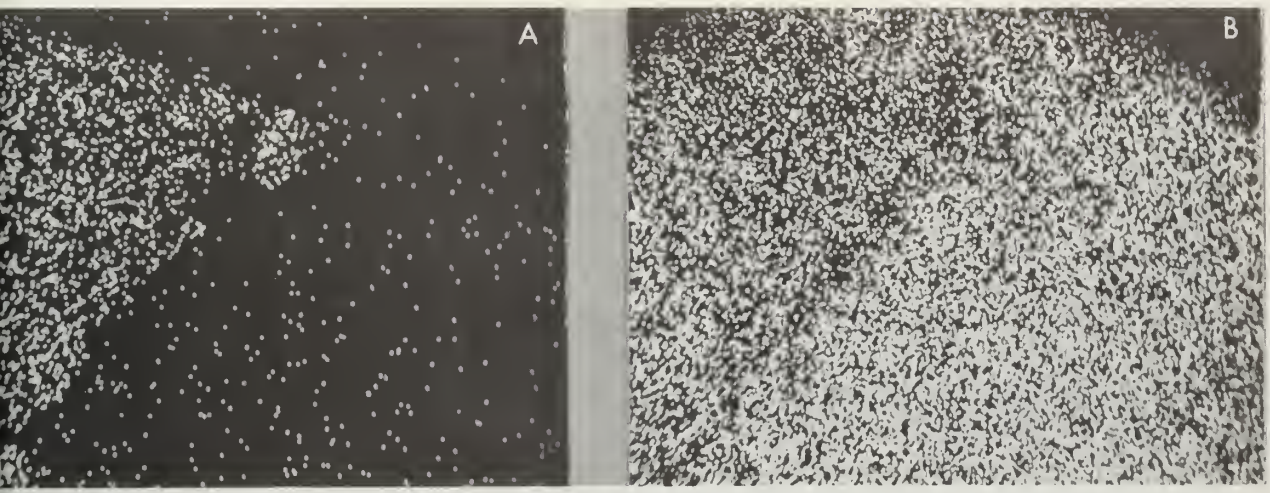
D. Poikilotopic dolomite. Although similar to C, the dolomite contains micron-sized inclusions of calcite (less than 10 percent of the rock) in addition to the darker, "dusty" inclusions, resulting in an inequigranular fabric. Again, "dusty" areas may overlap grain contacts. Dolomite grains are anhedral to subhedral and range from decimicron-sized (coarse) to centimicron-sized (fine to medium crystalline) fillings of coarser, clearer, but also poikilotopi mite are abundant, commonly with hazy bou because of neomorphism. Units 2, 3, and 4 this microfacies.

E. Micritic and peloidal limestone. Irregu rounded, grain-like peloids (McKee and Gutsch press) of micron to decimicron-sized (fine crys calcite are generally separated by xenotopic, granular, clearer, decimicron- to micron-sized (pls. 1H; 2A, B). Peloids range in size from medium sand, being most common in the grades. Boundaries are generally hazy and som posite peloids (grapestone) are present. Calcis circular to subcircular bodies averaging about 0 in diameter, contain equidimensional spar or ra crystals (pl. 1H). Larger, somewhat similar bo to 0.5 mm in diameter have micritic rims wh surrounded by decimicron-sized calcite orient pendicular to their surface (pl. 2C). These are ered to be trochiliscids by R. J. Stanton (writte munication, 1967). Included in this microfacies gradations to apparently nonpeloidal, micron-siz cite (pl. 2A, D) occasionally containing foss ments. As in microfacies C and D, pockets of spar give the appearance of a "micro" pseudo The microfacies occurs in units 2, 3, and 4, an dominant microfacies.

F. Bioconstructed carbonate. Textures, fabr composition of the groundmass overlap those o microfacies. *Amphipora,* and possibly some c roids, are commonly preserved as void fillig poikilotopic dolomite and calcite in a groundm xenotopic, decimicron-sized dolomite. These v ings are in places surrounded by a micritic en The most common groundmass of the stromat constructed limestones is the peloidal or micrit of microfacies E, although the limestone may b mitized as in microfacies H. Other than *Amp* clathyrodictyids, particularly *Hammatostroma,* most abundant stromatoporoids. These have w lined to relic laminae and pillars of micron-siz cite, the galleries being filled by xenotop equigranular, decimicron-sized (coarse crystall centimicron-sized (fine crystalline) calcite (p Silicification of stromatoporoids ranges fro existent through partial to complete. This mic occurs in units 2 and 3.

G. Quartzose, peloidal limestone and cal sandstone. Fine- to medium-grained quartz a crocline with rounded, clast-like peloids are ce by xenotopic, decimicron-sized (coarse crystall centimicron-sized (fine crystalline) calcite (pl. Detrital quartz grains, commonly strained b polycrystalline, have secondary overgrowths, s which include peloidal material (pl. 2H). Por greater than normal (less than 10 percent, ho Zircon and tourmaline are very rare. Units 3a contain this microfacies.

H. Dolomitized limestone. This microfa characterized by partial or nearly complete r ment by dolomite of limestone of microfacies E



7. X-ray Beam Scon Images, Dalamite Rhomb. Scans, by electron prabe, shaw MgKα (A) and CoKα (B) in dolomite rhomb (left side iotomicrographs) transecting a partian of peloidol limestone mottle. Both photogrophs X170; long diogonal of eoch = 320 micrans.

iotopic (idiotopic where against calcite), deci--sized (coarse crystalline) to centimicron-sized crystalline) dolomite replaces peloids, coarser calcispheres, and more rarely fossil fragments ., B, C, D). Calcite commonly occurs as mottles, nded by poikilotopic dolomite. Figure 7 shows beam scan images (with the electron probe nalyzer) of magnesium and calcium along the f such a mottle being replaced by a dolomite . Relatively rare silica, mainly as chert, has inclusions (pl. 3E, F). This microfacies is found s 3 and 4.

ightly dolomitic, calcareous sandstone and ose limestone. Well rounded, although badly ed, and well sorted, very fine- to medium-d, quartz and microcline grains float in or are ted by micron-sized calcite (p1. 3G) with some pic, inequigranular, decimicron-sized calcite, ning brachiopod, crinoid, and coral fragments. ae and irregular zones of chert engulf carbonate artz grains and include euhedral, decimicron-lolomite crystals (p1. 3H). The sporadic dolo-rystals in the groundmass of calcite are very ed. The microfacies is represented primarily by (Quartz Spring Sandstone Member).

Table 2. Relotion of Microfacies to Strotigraphy *

graphic unit	Microfacies
5 (Quartz Spring Member)	I
4	E, g, h, d, i
3	E, H, F, D, g, c
2	C, D, B, f, e
1 (Lippincott Member)	A, B

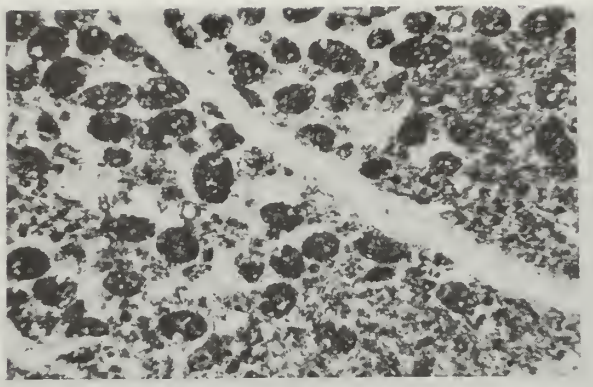
cies for each stratigraphic unit listed in decreasing order of rtance; lower case indicates microfacies that are rare in a cular unit.

Table 2 summarizes the relationship between microfacies and the stratigraphic units.

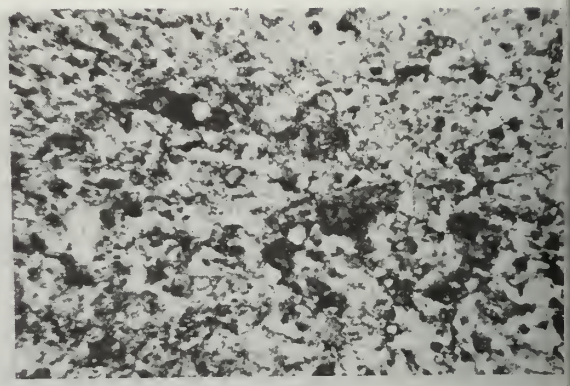
Generally, dolomite is coarser than calcite and grain contacts of the dolomite are less irregular. Microstyolites are not common, truncate certain structures such as fracture fillings (pl. 2C) and calcispheres, and are usually coated with limonitic or hematitic clay. Hematite also occurs as disseminated silt-sizes grains, or as larger blebs replacing organic material, and as euhedral grains after pyrite. There exist various generations of fractures, normally filled, some of which are "healed" —that is, carbonate grains now cut across them leaving a clear relic stringer in thin section. Porosity is low and exists primarily as void space along partings and stylolites. Clay minerals are rare in thin section, existing as the already mentioned coating on microstylolites, padding on carbonate grains in some irregular areas or laminations, and probably as the "dusty" inclusions in dolomite grains. Fractures in limestone and dolomite are commonly filled with secondary calcite and dolomite, respectively, but secondary calcite also occurs in fractures in many dolomites.

Discussion

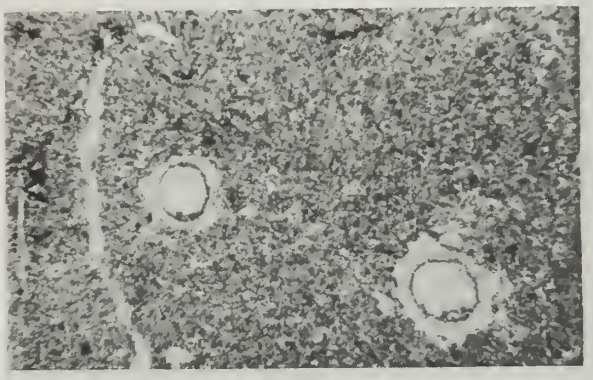
The term "calcisphere" has been used in a nongenetic sense to refer to the spherical bodies common in microfacies E (pls. 1H, 2D). Those with calcite centers showing a dark cross with crossed nicols (signifying radially oriented calcite crystals) may represent spherulites (Monaghan and Lytle, 1956, p. 111). Others with fillings of calcite spar not radically oriented may be neomorphosed spherulites or more probably mold fillings of dissolved spherulites—the spar does not cut across the micritic boundary. Stanton (1963) suggested that calcispheres probably represent some form of plant spore or reproductive body, although their exact affinity is uncertain. Pia (1937, original reference not seen; Stanton, 1963, p. 416) believed such structures were formed around gas bubbles but their stratigraphic restriction points against this hypothesis. Larger, less common but somewhat similar



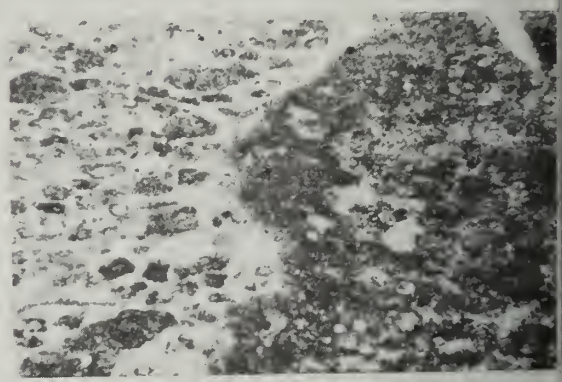
A



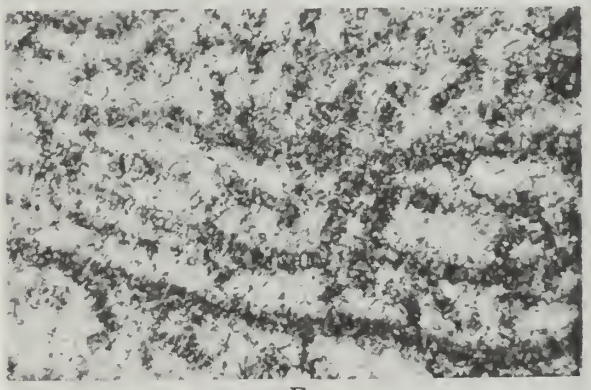
B



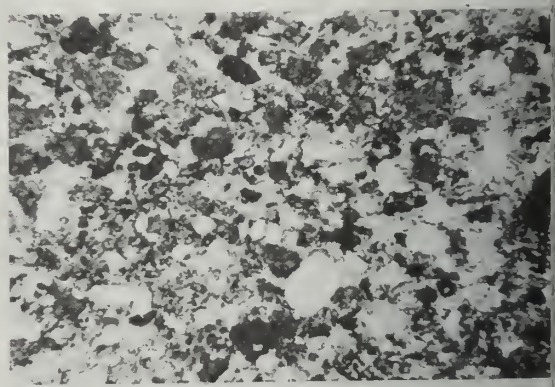
C



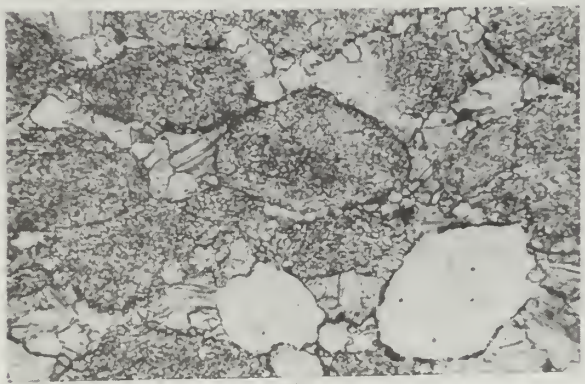
D



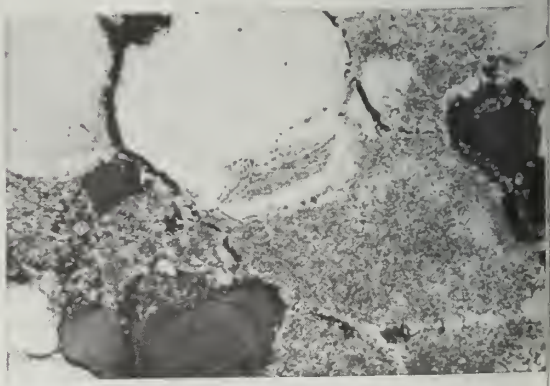
E



F



G



H

Plote 2. Photomicrographs.

oll photomicrographs ×20, length of short dimension = 2.8 mm; on oll photomicrographs ×80, length of short dimension = 0.7 mm.

d peloids groding into areo of closer packing of peloids; fracture fillings; microfocies E; strotigrophic "up" is to plone polorized light, ×20; unit 3.

A

Microfocies E; less regulor peloids in decimicron-sized colcite; plone polorized light, ×20; unit 3.

B

iliscids with micritic rims surrounded by rodiolly oriented note geopetol structure in trochiliscids, micron-sized ground- ond microstylolite cutting veinlet in upper left; microfocies dinory light, × 20; unit 2.

C

Microfocies E; possage from peloidol areo into one of "merged peloids"; note calcispheres; plone polarized light, ×20; unit 4.

D

otoporoid-constructed limestone of microfocies F; plone ized light, ×20; unit 3.

E

Sondy, peloidol limestone of microfocies G; plone polorized light, ×20; unit 4.

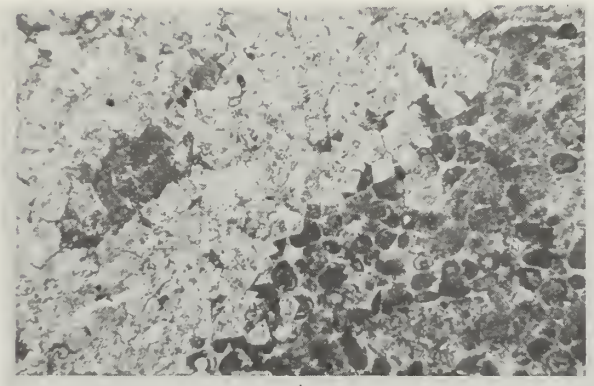
F

outlined, sand-sized peloids of micron-sized to decimicron- (fine crystolline) colcite ond quortz groins in clear colcite nt; microfocies G; plone polorized light, ×80; unit 3.

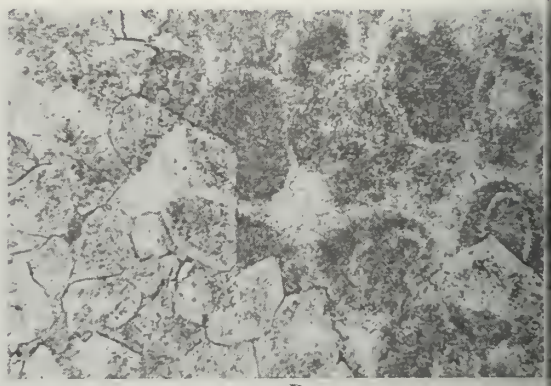
G

Secondory overgrowth on quortz groin enclosing part of neighboring peloid; microfocies G; crossed nicols, ×80; unit 3.

H

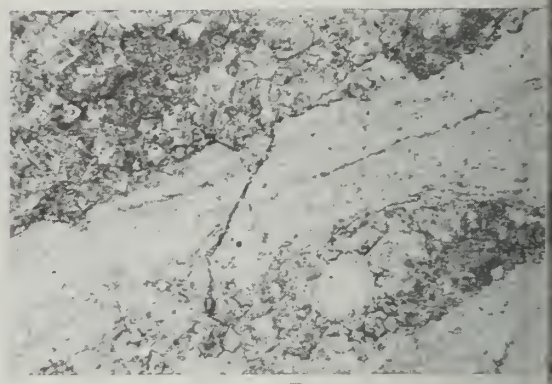


A

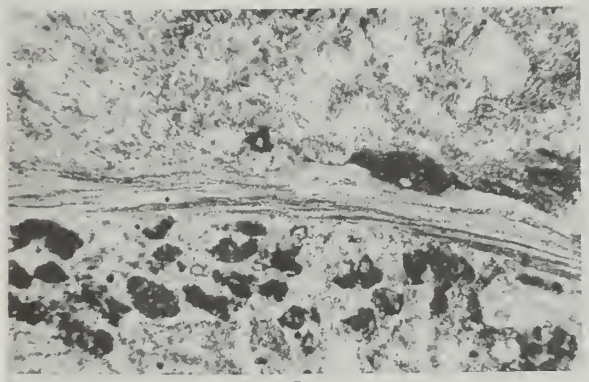


B

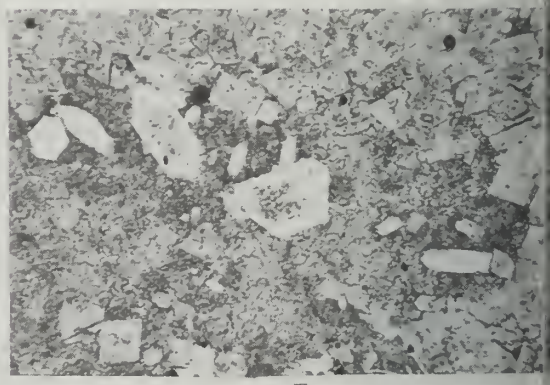
C



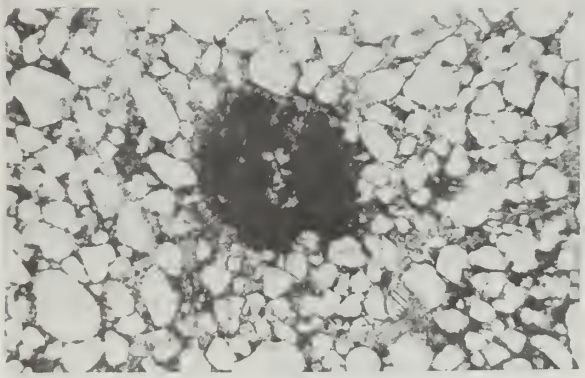
D



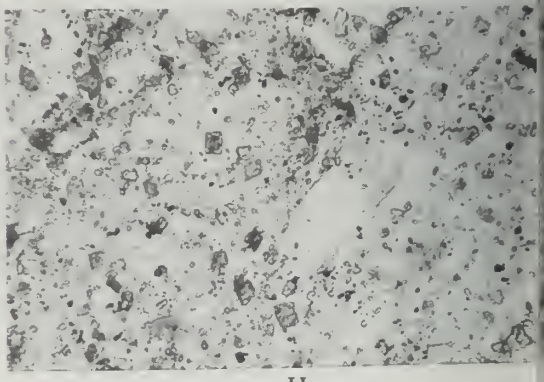
E



F



G



H

Plate 3. Photomicrographs.

l photomicrographs ×20, length of short dimension = 2.8 mm; an oil photomicrographs ×80, length of short dimension = 0.7 mm.

opic, hypidiotopic dalamite (light) replacing peloidol ne; dolomite idiotopic against colcite; microfocies H; y light, ×20; unit 3.

A

Enlargement of part of 3A showing the transection and inclusion af pelaids by idiatopic, poikilotopic dolomite (light); microfacies H; plane polarized light, ×80; unit 3.

B

izotion of peloids and calcisphere; microfacies H; plane ed light, ×80; unit 3.

C

Microfacies H; dolomitization of graundmass more odvanced than that af bachiopod shells; plone polorized light, ×80; unit 3.

D

patch of chert (light potch in center of figure) replocing brachiopod shell in peloidol limestone of microfocies H; polorized light, ×20; unit 3.

E

Replacement of peloidol limestone by euhedrol, outhigenic quortz ond idiotopic dolomite; note inclusions of colcite in chert; micrafocies H; plone polorized, ×80; unit 3.

F

eous sondstone of Quartz Spring Sandstone Member (mies I); note hemotitizotion of crinoid frogment; ordinary ×20; unit 5.

G

Chert of Quartz Spring Sandstane Member (microfocies I) with calcite inclusions, dolomite euhedro, a few quorttz groins, ond disseminated hemotite groins; plone polorized light, ×20; unit 5.

H

structures in microfacies E (pl. 2C) probably are trochiliscids (R. J. Stanton, written communication, 1967), bodies which Peck (1934) considered to be fossilized charophyte zygotes. Some of these contain geopetal structures.

The term "peloidal limestone," introduced by McKee and Gutschick (in press), and so far as we know first mentioned by Bathurst (1966, p. 21), is used descriptively to refer to a fabric consisting of round or irregular areas of micron-sized (more rarely decimicron-sized) calcite, or "peloids," in a matrix of decimicron- to centimicron-sized calcite spar. "Peloidal" connotes no size limitations nor does it imply any particular genesis, thus making it a very useful general term to include such varieties as "structure pseudoolithique" of Cayeux (1935, p. 267–271), "clotted limestone" of Wood (1941, p. 195), "bahamite" of Beales (1958, p. 1846), "pelletal limestone" of many workers, and others. These terms usually convey a particular genesis. The present writers agree with Beales (1965, p. 52) in feeling that it is often difficult to distinguish between these varieties and that many peloidal limestones are probably polygenetic; such situations substantiate the need for this new term.

Many suggestions have been made with regard to the origin of peloids and the peloidal fabric. Illing (1954, p. 26–28) proposed that ovoidal sand-sized grains of cryptocrystalline matrix, found in the Bahamas, resulted from the cementation of originally irregular and friable aggregates of agglutinated silt and mud particles. "Clotted limestone" refers to recrystallization within a micrite leaving relic patches of the micron-sized material within a matrix of coarser spar (Wood, 1941, p. 195–196; Carozzi, 1960, p. 209). "Pelletal" commonly is taken to mean that the bodies of micrite, usually round in this case, represent fecal pellets. However, Beales (1965, p. 49) included under the term "pelletted" material that has been assembled by some form of organic or inorganic agglutinization. Wolf (1962, p. 247) described grains of algal origin from the Nubrigyn Limestone (Devonian) of Australia which resemble the bahamite of Beales. Bathurst (1966, p. 21) showed that a process of micritization of skeletal grains by boring algae could produce such peloids. Certain writers, including McKee and Gutschick (in press), consider that many peloids, particularly those ovoidal in shape, are intraclasts derived from nearby carbonate mud.

In the Lost Burro Formation, peloids vary in shape from round and, in places, elliptical, to irregular. Some of the elliptical peloids (pl. 2A), commonly in the medium sand-size range, are very similar to modern fecal pellets from the Bahamas but this origin cannot be proven. Certainly Folk's (1959, p. 7) restriction of the term "pellet" to those bodies below 0.15 mm in greatest diameter seems inappropriate because modern marine fecal pellets are commonly larger. Illing (1954, p. 24) reported that the longest diameter of fecal pellets from Ragged Island Concession samples (Bahamas) lies between 0.5 and 0.7 mm. Although it cannot be disproven that the peloids are algal grains, the apparent lack of any recognizable algal material would make such a conclusion tenuous indeed. Micritization, as described by Bathurst (1966), seems very unlikely as a contributing process to Lost Burro peloids of Recent Bahaman micritized skeletal fragme amined by the senior author through the cour R. G. C. Bathurst showed all gradations from p micritized and relatively well preserved skeleta rial to completely micritized and completely crystalline aragonite. No such gradation occurs the peloidal fabric of the Lost Burro Formati the rare fossil fragments, with the exception sible micritic envelopes around *Amphipora* v ings, are not micritized in the least. It is doubt this peloidal fabric has resulted solely throug morphism. As pointed out by Bathurst (writte munication, 1968), it would seem that as neomc proceeds, discrete and round relics of micr material would be unlikely; however, that s the irregular peloids formed in this way can sidered a possibility.

It is highly probable that Lost Burro pelo polygenetic. As noted above, some appear to pellets. Other irregular to round, but nonellipt loids, may have resulted from accretion of m silt as proposed by Illing (1954, p. 26–28). Ye Lost Burro peloids may represent intraclasts, a it is questionable whether contemporaneous ca mud would be sufficiently hard to provide cla

The sparry interareas between peloids are ered to represent cement precipitated in void within the predominantly grain-supported Bathurst (1959, p. 368; oral communication, 19 Beales (1965, p. 56) have stressed the difficul volved in distinguishing between precipitated cement and neomorphic spar. The grain conta are very irregular, suggesting a neomorphic, than a precipitated, origin. The criterion o boundary shape alone, however, is not concl is possible that some neomorphism occurred the cement, resulting in a migration of grain aries and the development of irregular contacts, as an increase in grain size.

Some samples include an abrupt transition peloidal fabric to a more homogeneous, micr field, which on close examination commonly close packing of peloids and practically no inte spar (pl. 2D); this fabric resembles the merge of various authors and the "structure grumele Cayeux (1935, p. 271–272, fig. 67). The origin areas is conjectural. Although it is felt here th morphism is not the primary cause of the fabric, such a process could explain the "mer loidal" areas simply through a lack of recrystal Or, possibly, closer packing of the peloids res a lack of void space for precipitation. It is that compaction, which theoretically coul forced peloids into a tighter packing arran could have caused such an abrupt transition. T tively sharp contact may represent an erosio face, the more homogeneous material providi for the peloidal fabric. Conceivably, some micrite may be more susceptible to erosion be less efficient binding by mucilaginous material to that reported by Bathurst (1967b). Bec many samples, elongate peloids parallel the b have distinct margins (pl. 2G), and are well

ovement is suggested. It must be kept in mind, r, that fecal pellets would naturally tend to be ted. Still, the presence of quartz grains and correctly interpreted as cement, strongly sug- ne turbulence as these particular layers formed.

placement origin for dolomite in mixed car- of microfacies H is indicated by idiotopic and opic dolomite transecting peloids, calcispheres, ils (pl. 3A, B, C, D). In microfacies D, the opic fabric (calcite inclusions) provides evi- or replacement. In some noncalcareous dolo- dusty" areas, perhaps representing pre-existing overlap grain boundaries (pl. 1F). The pres- microfacies B and C of zoned dolomite crys- 1C, D) suggests a local source dolomitization ibed by Murray (1964, p. 399–403). The rela- lear rims may represent void filling by dolo- a moat formed about the growing rhomb. This uld result from the extra solution outside the e necessary to account for the 13 percent de- n volume of dolomite vs. calcite that would rom replacement. Numerous occurrences of rical shadowy rhombs within the zoned crys- gest a lack of effective compaction at the time formation. This could be accounted for if the us material being replaced had achieved a cer- ree of early lithification, which seems to have e case for many limestones. The presence of us dolomite beds with calcitic stromatoporoids very early, probably penecontemporaneous ization of the matrix without a significant ef- the stromatoporoids. In other beds containing agments it is quite apparent that the finer matrix was selectively dolomitized (pl. 3D). icrite and spar appear equally susceptible to nent. That dolomitization in places continued diagenesis is indicated by dolomite euhedra ing secondary spar of some void fillings.

bodies contain inclusions of calcite and outlined dolomite rhombs (pl. 3H) which y are smaller and less corroded than the beyond the chert. As in the case of the Knox e (Dietrich and others, 1963), it appears that s engulfed carbonate areas, replacing calcite rrupting dolomitization.

Environment of Deposition

nents regarding the environments of deposition se must be provisional. Although the recon- e work done to date along the outcrop belt suggests there will be relatively little change ature of the microfacies, their exact distribu- ot known with certainty. The determination eline geography and paleoslope characteristics end upon subsequent petrological analysis of at other localities. A further complication is eral paucity of fossils which are so vital in a logical analysis. Furthermore, the writers are overspeculation when using only textural evi- uch as grain: micrite ratios, in carbonates which notorious for their neomorphism. Bathurst has indicated the dangers inherent in attempt- ing to specify depths of carbonate sedimentation. Two of the more conclusive pieces of evidence of very shallow water deposition, oolites and stromatolites, are lacking in the Lost Burro Formation at the type locality (possibly thin oolitic films are present in some peloids, e.g. pl. 3B). No algae were observed.

The micritic and peloidal limestones (microfacies E) bear strong resemblance to the description of certain sediments of the Bahama Banks (Illing, 1954) and to ancient bahamites described by Beales (1956, 1958) in having similar textures, relatively low megafossil content, generally low porosity, few oolites, and massive bedding. Carss and Carozzi (1965) described similar characteristics such as pellets, calcispheres, and *Amphipora* biostromes, from Upper Devonian limestones (approximately equivalent to units 3, 4, and 5) in the Arrow Canyon Range, Nevada. They presented an analogy with the present Florida Bay area. Beales (1958, p. 1866–1867), comparing certain bahamites, such as the Devonian Palliser Limestone of Alberta, concluded that these older deposits probably formed on marine shoals covered by but a few feet of water, where water turbulence was insufficient to roll grains continuously and they tended to cement together. The presence of calcispheres in this microfacies may further suggest a shallow-water, low-turbulence environment. Although they are known occasionally from basinal facies, they are most typical of shallow water deposition (R. J. Stanton, written communication, 1967). However, unlike Beales' typical bahamites, some Lost Burro peloidal limestones are very quartzose and grade to calcareous sandstone (microfacies G), suggesting a nearby source of terrigenous matter and sufficient turbulence to move the sand grains. It is in such rocks that the rounded peloids show most indication of having undergone some movement, although elongate fecal pellets would normally be oriented with their long axes parallel with the bedding. These calcareous sandstones and peloidal quartzose limestones are lacking in calcispheres. Slight uplift probably resulted in the intercalation of the higher-energy quartz-rich beds with the more offshore, quiet-water micritic and peloidal limestones.

The bioconstructed microfacies (F), primarily in units 2 and 3, occurs as biostromes with *Amphipora* and hemispherical stromatoporoids being the main contributors. No mound-like "reef" structures were observed, so neither of these acts as true frame builders at this locality. By virtue of their low terrigenous content, these beds probably represent shallow water, relatively offshore deposition. Murray (1966, p. 16–19), considered hemispherical stromatoporoids as significant frame builders that thrived in shallow turbulent water, whereas *Amphipora* represented sheltered, slightly restricted waters of a back reef environment. Jenik and Lerbekmo (1968, p. 34–37) also considered hemispherical stromatoporoids as high-energy indicators and *Amphipora* as probably indicative of a quiet-water environment. In the Lost Burro Formation, these two kinds of stromatoporoids usually are in separate beds, although commonly they occur immediately adjacent to one another and in places are mixed together, indicating a similar ecology. Their close asso-

ciation, coupled with a common matrix of micritic and peloidal limestone low in terrigenous content, but containing rare fossil fragments (mainly of brachiopods) in some bioconstructed beds, suggests a moderate-turbulence environment. This turbulence may also be suggested by hemispherical stromatoporoids which are not in growth position.

Two possible conditions for dolomitization often referred to are proximity to shore, where Mg-Ca ratios reportedly are higher, and hypersalinity. Friedman and Sanders (1967, p. 267–268) considered dolomites as evaporite deposits, with very few exceptions. The relatively poor faunal content, except in Microfacies F and I (bioconstructed carbonate and slightly dolomitic calcerous sandstone and quartzose limestone microfacies, respectively), may indicate partial restriction of the Lost Burro sea. Jenik and Lerbekmo (1968, p. 40) interpreted calcispheres as representing a very shallow-water environment with restricted circulation. No unequivocal evaporites were observed in the Lost Burro Formation, however, and it is dubious that salinities were much above normal. Nor are there evaporitic units immediately above the Lost Burro that might suggest seepage refluxion as a possible mechanism of dolomitization. The effect of dolomitization decreases upward in the Lost Burro as attested by the strongly dolomitized microfacies (A–D) low in the formation and less dolomitization in the higher microfacies H and I. Even within microfacies A–D there is a suggestion of decreasing completeness of dolomitization upward. In microfacies A and B, dolomitization is essentially complete and no relic limestone textures or structures are recognizable. In the fine dolomite of microfacies C, which for the most part occurs higher than microfacies A and B, are areas of dusty inclusions which commonly transcend the boundaries of the dolomite grains and possibly represent relic peloids. The same pattern can be seen in the poikilotopic dolomite of the yet higher microfacies D, a considerable portion of the inclusions being calcite. This tendency toward less severe dolomitization upward is further reflected by the stratigraphically higher dolomitized limestone (microfacies H), in which are variously sized areas (inches to millimeters) of undolomitized limestone, and by the scattered dolomite rhombs of microfacies I (Quartz Spring Sandstone Member), which represent early diagenetic dolomitization interrupted by silicification. The high quartz content and cross bedding of microfacies A and the coarse-grained (centimicron-sized) dolomite of microfacies B probably represent a shallow water, high-energy environment, although the coarser spar could have resulted from neomorphism in conjunction with metasomatism. One might argue that the decrease in severity of the dolomitization in the overlying microfacies is owing to a more offshore, lower energy environment; these dolomitized microfacies contain evidence of relatively quiet-water textures (e.g., peloids, calcispheres, etc). However, if one were to attempt to correlate extent of dolomitization with terrigenous content and nearness to shore, the lack of dolomite in the peloidal calcareous sandstones (microfacies G) and the but-slight dolomitization of calcareous sandstones of microfacies I (Quartz Spring stone Member) must be questioned. No ans apparent for the lack of dolomitization in mici G but, very possibly, early silicification pre more pervasive dolomitization in the Quartz Sandstone Member. It should be recalled tl earlier-mentioned study of the relation of in content vs. dolomite percent showed no stati significant correlation between these parameter

CONCLUSIONS

It is quite certain that the type Lost Burro tion is equivalent to Hazzard's (1937, 1954) " Limestone of the Nopah Range, to Hamill's Nevada and Devils Gate Formations of the Mt. area north of Pahrump, Nevada, and to the Goodsprings Dolomite and Sultan Limestone o ett (1931) in the Mountain Pass, California, and springs, Nevada, areas. Because of similarities b units in the vicinity of the California-Nevada appears that a stratigraphic revision will be p eventually.

Carbonates of the Lost Burro in the vicinity type locality are sandwiched between clastics basal and uppermost portions. Regression cc suggested above the low-insoluble Hidden Dolomite, followed by transgression which l into the area the lower energy, farther offsh micritic and peloidal limestone microfacies fc stratigraphic units 2, 3, and 4. Regression ma occurred in the upper part of the Lost Burro tion, ending with the Quartz Spring Sandstone ber, which is overlain by the low-clastic Tin tain Limestone. On the other hand, clastic ur beds may represent sporadic uplifts in the sou resulting in the influx of terrigenous material causing widespread movement of the shoreline a manner similar to that described by Sand Friedman (1967, p. 224), the introduction of grains into a carbonate depositional province m resulted from longshore transportation of terr material, as is occurring presently along the ea of Florida. Subsequent statements in this regar further work across the outcrop belt.

The area under discussion would generally sidered as miogeosynclinal in tectonic setting the middle Paleozoic. Stratigraphic and petrolo dence in the limestones of the Lost Burro Fo suggests a shelf-type environment. Cross- quartzites associated with dolomite of the Lip Member coupled with relic textures and fabric dolomites also suggest a near-shore, shallow-wa Assuming there are no conspicuous unconfo thicknesses are also in line with shelf sedime The evidence suggests that, as is not uncomm ing periods of relative tectonic quiescence, tl geosyncline was shelf-like in nature.

The apparent similarity of stratigraphic anc logic characteristics in Upper Devonian lin equivalent to the upper Lost Burro Formati gests extremely widespread yet relatively unifo ditions of deposition during this interval in the leran miogeosyncline and shelf.

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D METHOD OF SAMPLING DIATOMACEOUS EARTH*

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ABSTRACT

tively rapid and simple method of sampling dia-us earth consists of impressing a strip of common ummed tape against the surface of the diatomite oving a thin layer of particles for microscopic ex-n.

INTRODUCTION

examination of diatomaceous earth under the ope yields certain data that cannot be gained means. Knowing the shapes and sizes of dia-e relative abundance of each type and the s of admixed rock and mineral fragments helps aising the economic value of diatomaceous he recognition of diatom species and diatom ges also may supply data on paleoecology and age. However, the properties of diatomaceous n be strikingly different from place to place he same bed and from one bed to another. ently, the comparison between the relatively nount of diatomaceous earth that can be ob-hrough the microscope and the much greater of material actually being studied is com-o disproportionate that it is difficult and time ng to collect and examine representative . Moreover, the standard collecting and prepa-echniques disturb the spatial and abundance hips between diatoms of different species and and any other materials in the sample.

MATERIALS NEEDED

Field

oll of single gummed, translucent plastic tape, ne-half inch wide (for sampling).
rips of relatively stiff, clear cellulose acetate, ree-quarter inch by 12 inches (for mounting e sample tape).
lasons hammer (chisel head).
iff brush.
ape measure.
mall nails.
abels.

pt submitted for publication January 1969.

Laboratory

8. Glass atomizer.
9. Hyrax (commercial high index (RI 1.65) mounting compound).
10. Xylene.

FIELD PROCEDURE

A relatively flat, shallow channel is cut in the outcrop with a masons hammer. The channel is cut normal to, or parallel with, the bedding, depending upon the desired objective of the sample. One-foot increments are laid off along the side of the channel and marked by nails (fig. 1). With a stiff brush the channel is swept clean of loose material. The sweeping should begin at the upper part of the channel and proceed downward using only down strokes. About one foot of gummed tape is pressed evenly against the outcrop at the top of the channel. The top end of the tape is held by one hand while the thumb of the other hand gently smooths it down along the channel. The tape is lifted off the outcrop and pressed onto a stiff clear plastic strip. The plastic strip is labeled in proper stratigraphic order or other sequence and protected for transportation to the laboratory.

LABORATORY PROCEDURE

The gummed tape is stripped off the stiff plastic strip leaving a thin layer of diatomaceous earth adhering to the strip. The thin layer of particles is apparently held electrostatically to the plastic strip. Using a solution of Hyrax diluted with xylene in a glass atomizer, a thin coating is sprayed onto the plastic strip, anchoring the particles. After allowing the coating to dry for an hour or more, depending upon atmospheric conditions, the strip then constitutes a slide that may be examined directly under the microscope. The coating is resistant to corrosion from the common immersion liquids used with high power objectives (castor oil, glycerine, etc.). The slides appear to be relatively permanent, but after continual flexing the coating may become checked.

Figure 1. Field Procedure.

DISCUSSION

The physical properties of diatomaceous rocks range so widely that it is seldom possible to take a continuous sample using this method. The tape may pluck relatively large fragments from the outcrop that will not adhere to the clear plastic strip, and that section of the record will be incomplete. Also, the fragments that do adhere will represent a wide size distribution, ranging from individual diatoms, or broken segments, to opaque aggregates of diatoms and other impurities, leading to further imperfection in the record. However, any of the sampled fragments that do not adhere to the clear plastic strip will still be preserved in proper relative position on the gummed tape. Thus, the missing parts of the record can be restored, if necessary, by making separate slides of these fragments.

Normally, taxonomic determinations can be made from the slides produced by this method. However, where only a few individuals of the same species are represented, their orientation may not reveal a cient number of diagnostic features to allow i cation.

This technique is most useful for the samp diatomaceous earth where the general nature sible economic value is to be determined. The r with which a representative sample can be ol and the preservation of both the spatial relati and compositional ratios are the most valuable f of the method. Moreover, a nearly complete of an outcrop can be transported to the lab and stored in only a fraction of the space that mally required for hand specimen or channel s

The method could be used solely in the lab to make any desired length of microscopic slid a bulk sample of diatomaceous earth. It also m used to sample fine grained rocks other than di ceous earth, such as claystones.

△78589—650 3-69 3,400

2796

EXPLANATION

Unconsolidated sedimentary deposits
Qp, *playa lake surface deposits*
Qs, *windblown sand*
Qal, *alluvial deposits*
Ql, *Pleistocene lake deposits*
Qg, *old gravels, now being dissected*

Christmas Canyon Formation
Lake silts and sands

Volcanic and sedimentary rocks
Tv, *volcanic rocks, mostly basalt and andesite, a little dacite*
To, *pyroclastic rocks*
Ts, *sedimentary rocks*

Plutonic rocks
Quartz monzonitic rocks. Divided into five numbered units, on the basis of areal extent, composition, and texture, which are indicated on the map by subscripts

Shale

Metavolcanic rock
Mv, *metavolcanic rocks*
Mvs, *schistose metavolcanic rocks*

Marine sedimentary rocks
Ps, *sedimentary rocks, restricted to area south of Garlock fault*
Pl, *limestone and marble, restricted to north end of range*
Pq, *quartzite and dolomite, exposed in Panamint Range east of Panamint Valley fault zone*

Metamorphic rocks
pCmu, *metamorphic rocks, undivided*
pCms, *metasedimentary rocks, exposed only near Gold Bottom and Ophir mines*
pCmp, *metaplutonic rocks, restricted to west side of range*
pCmsc, *schist, some gneiss and slate*

Pleistocene to Recent
Pleistocene(?)
QUATERNARY
TERTIARY
MESOZOIC
PALEOZOIC
PRECAMBRIAN

Contact
Dashed where gradational or approximately located; queried where doubtful

Fault, showing dip
Dashed where indefinite; dotted where concealed; queried where doubtful. Bar and ball on downthrown side

Low-angle fault
Dashed where indefinite; dotted where concealed; queried where doubtful. Sawteeth on upper plate

Shear zone, showing dip

Strike and dip of beds

Strike and dip of foliation

Landslide

Location of radiometrically dated rock

Gravity contours
Contour interval is 5 milligals. Hachured contours indicate areas of low gravity closure

Gravity stations
Values are complete Bouguer anomalies plus 1,000 milligals. Open circles are stations established during this study; station numbers relate data to table 3. Solid circles are data from Mabey (1963)

SCALE 1:62,500
0 1 2 3 4 5 MILES

CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL

Gravity contours

Contour interval is 5 milligals. Hachured contours indicate areas of low gravity closure

893 / 10 — 873

Gravity stations

Values are complete Bouguer anomalies plus 1,000 milligals. Open circles are stations established during this study; station numbers relate data to table 3. Solid circles are data from Mabey (1963)

SCALE 1:62,500

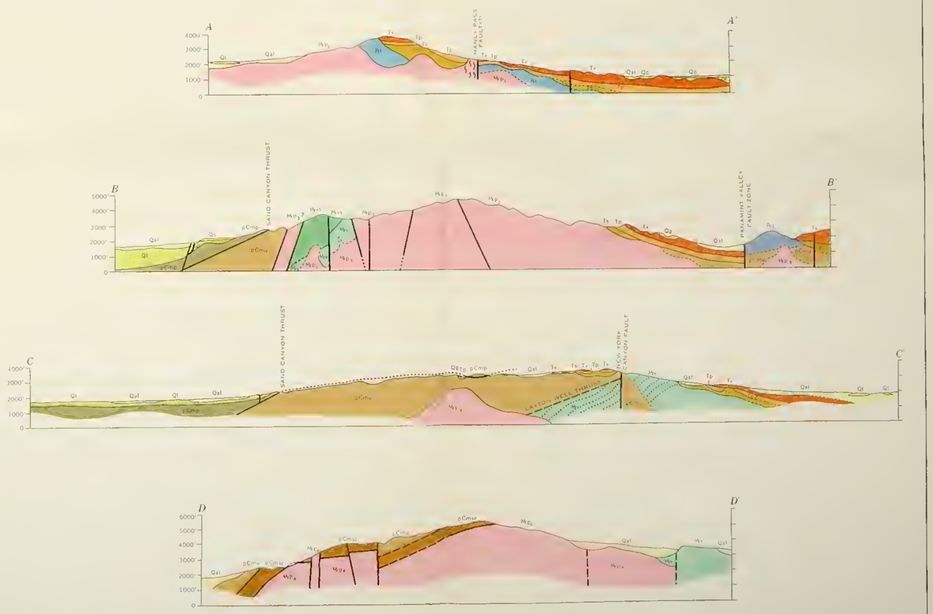
0 1 2 3 4 5 MILES

CONTOUR INTERVAL 40 FEET

DATUM IS MEAN SEA LEVEL

INDEX MAP

0 100 MILES



Base from U.S. Geological Survey topographic quadrangles

Geology mapped by George I. Smith, Bennie W. Troxel, Clifton H. Gray, Jr., and Roland von Huene, 1960–1965. Assisted in 1962 by Ralph L. Langenheim, Jr. and James D. Ridlon. Gravity survey by Roland von Huene.

RECONNAISSANCE GEOLOGIC MAP OF THE SLATE RANGE, CALIFORNIA

DIVISION OF MINES AND GEOLOGY
IAN CAMPBELL, STATE GEOLOGIST

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF CONSERVATION

SPECIAL REPORT 97
PLATE I

GEOLOGIC MAP OF SAN FRANCISCO BAY AREA

LEGEND

SEDIMENTARY AND METASEDIMENTARY ROCKS

QUATERNARY

- Qs — Sand dunes
- Qal — Alluvium
- Qb — Basin deposits
- Qm — Pleistocene marine and marine terrace deposits
- Qc — Pleistocene non-marine
- QP — Plio-Pleistocene non-marine

TERTIARY

- Pc — Pliocene non-marine, undivided
- Pu — Upper Pliocene marine
- Pmlc — Middle and lower Pliocene non-marine
- Pml — Middle and lower Pliocene marine
- M — Miocene marine
- Φ — Oligocene marine
- E — Eocene marine
- Ep — Paleocene marine

JURASSIC CRETACEOUS

- K — Cretaceous marine, undivided
- Ku — Upper Cretaceous
- Kl — Lower Cretaceous
- JK — Knoxville Formation

Franciscon Formation, undivided (KJf)

- KJfv — Franciscon volconic rocks
- gr — Granitic rocks
- ub — Ultro-basic rocks

- G — Grovel and sand
- S — Sand
- Mud — Mud
- Sh — Shell and mud

IGNEOUS AND META-IGNEOUS ROCKS

- Pv — Pliocene volcanic rocks

SYMBOLS

- Observed fault
- Inferred fault
- Contact
- Submarine contacts

Geology adapted from California Division of Mines and Geology Geologic Map of California on a scale of 1:250,000, and Trask (1953).

Compiled by James E. Kahle and Harold B. Goldman

2 1 0 2 4 6 8
scale in miles

August, 1966

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PLATE 2

CONTOURS ON THE TOP OF THE BEDROCK UNDERLYING SAN FRANCISCO BAY

EXPLANATION

——— Contours where control is good
– – – – Inferred contours

Contour interval 20 feet
Datum is mean lower low water

SOURCE:
California Division of Mines and Geology-1966
Compiled by James E. Kahle and Harold B. Goldman

Adapted from U. S Army, Corps of Engineers, Appendix "E", 1963.
Revisions from: Schlocker, J., 1962; Bonilla, M. G., 1964; Schlocker, J., et al., 1958; Radbruch, D. H., 1957; Weaver, M. A., and Radbruch, O. H., 1960; and others.

SAN PABLO BAY
SAN FRANCISCO BAY
SUISUN BAY
GRIZZLY BAY
POTRERO HILLS
MARTINEZ
BENICIA
RICHMOND
BERKELEY
OAKLAND
ALBANY
EMERYVILLE
PACIFIC OCEAN
SAN PABLO
PITTSBURG
ANTIOCH
DENVERTON
SUISUN
SIMMONS ISLAND
WHEELER ISLAND
VAN SICKLE ISLAND
BROWNS ISLAND
GRIZZLY ISLAND
HONKER BAY
SACRAMENTO RIVER
SOLANO WTR
SAN PABLO
PORT CHICAGO
MARE ISLAND
TIBURON PENINSULA
ANGEL ISLAND
SAN RAFAEL
SAUSALITO
POINT CONTE
MONTEZUMA SLOUGH
CHIPPS ISLAND
DUTTON ISLAND
RIVER ISLAND
MONTEZUMA HILLS

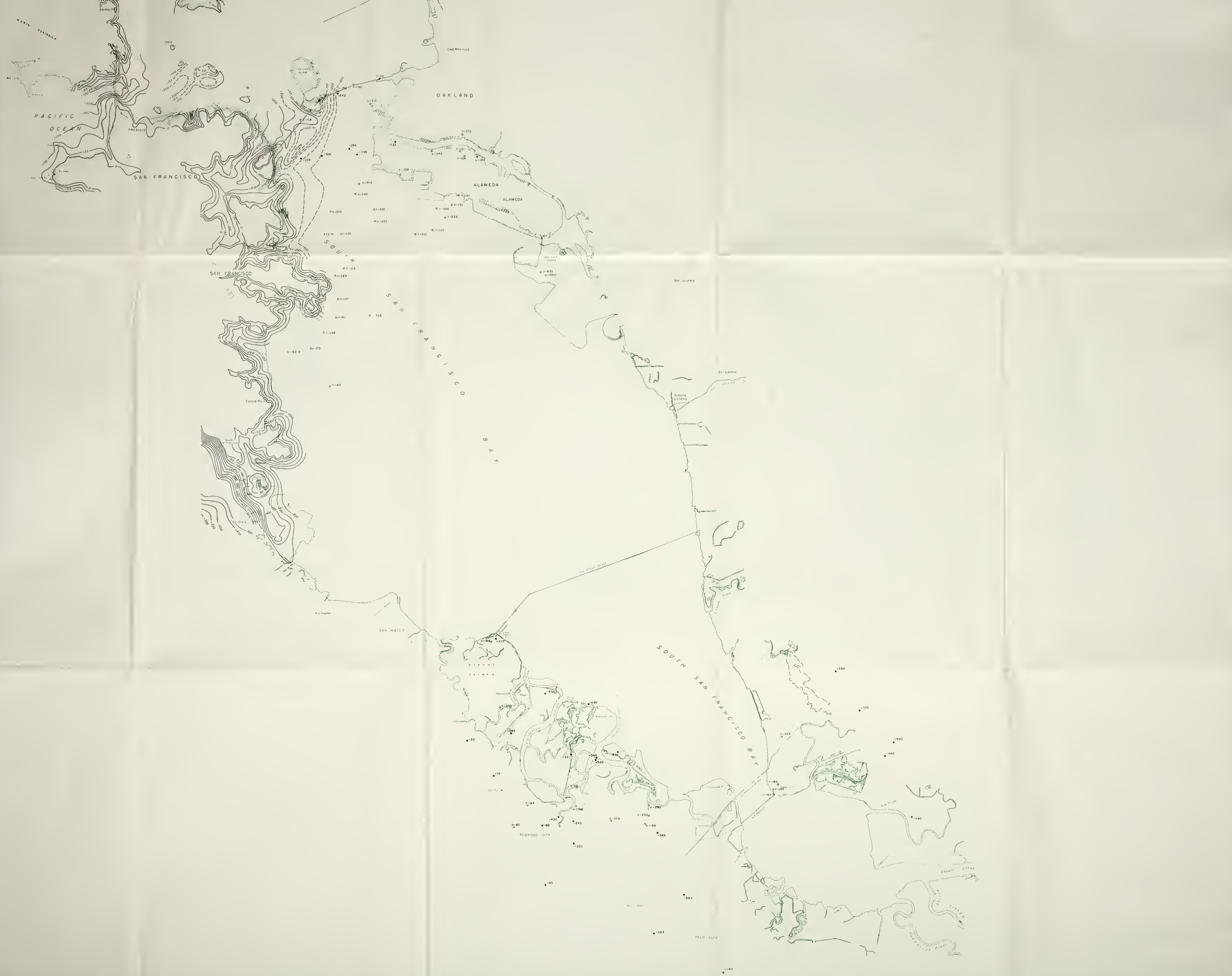

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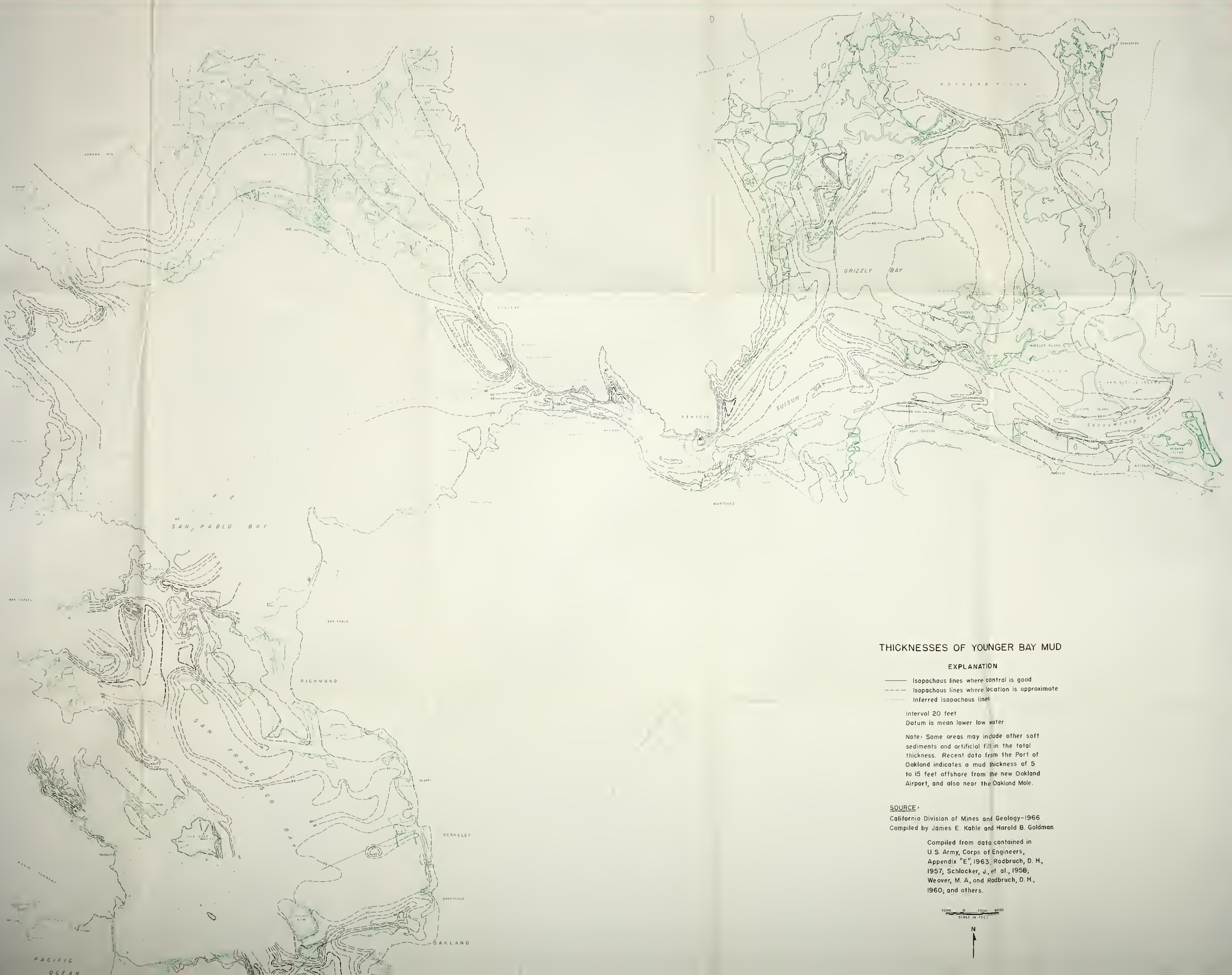
PLATE 4



THICKNESSES OF YOUNGER BAY MUD

EXPLANATION

——— Isopachous lines where control is good
– – – – Isopachous lines where location is approximate
····· Inferred isopachous lines

Interval 20 feet
Datum is mean lower low water

Note: Some areas may include other soft sediments and artificial fill in the total thickness. Recent data from the Port of Oakland indicates a mud thickness of 5 to 15 feet offshore from the new Oakland Airport, and also near the Oakland Mole.

SOURCE:
California Division of Mines and Geology–1966
Compiled by James E. Kahle and Harold B. Goldman

Compiled from data contained in U. S. Army, Corps of Engineers, Appendix "E", 1963, Radbruch, D. H., 1957; Schlocker, J., et al., 1958; Weaver, M. A., and Radbruch, D. H., 1960; and others.

5000 0 5000 10000
SCALE IN FEET

N

Compiled from data contained in
U. S. Army, Corps of Engineers,
Appendix "E", 1963, Radbruch, D. H.,
1957; Schlocker, J., et al., 1958;
Weaver, M. A., and Radbruch, D. H.,
1960; and others.

3000 0 3000 6000
SCALE IN FEET

N

PACIFIC OCEAN

SAN FRANCISCO

OAKLAND

BERKELEY

EMERYVILLE

ALAMEDA

SAN FRANCISCO BAY

SOUTH SAN FRANCISCO BAY

SAN MATEO

REDWOOD CITY

PALO ALTO

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PLATE 3

CONTOURS ON THE BOTTOM OF THE YOUNGER BAY MUD

EXPLANATION

——— Contours where control is good
– – – – Inferred contours
····· Intermediate contours

Contour interval 20 feet
Datum is mean lower low water

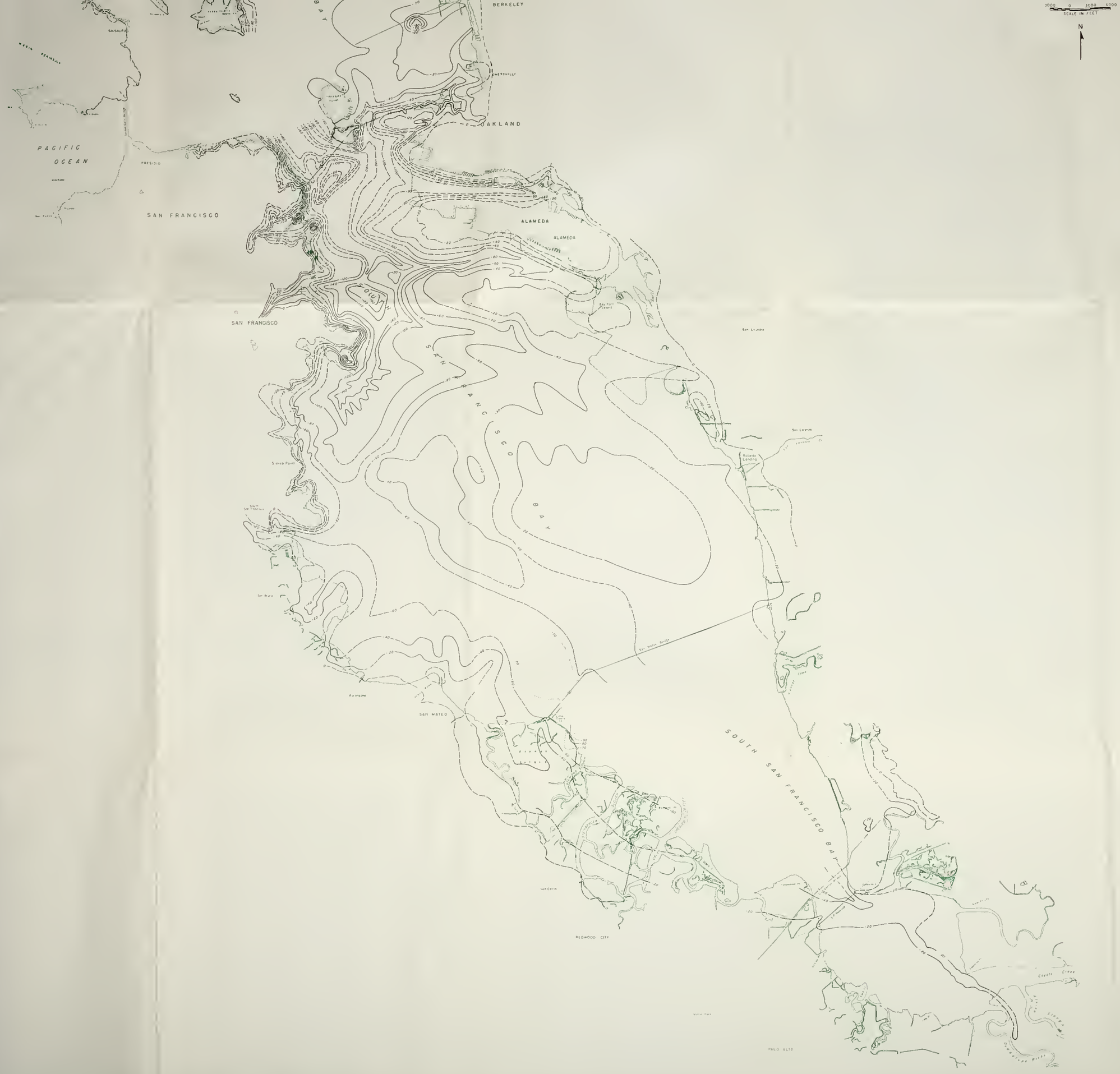
SOURCE:

California Division of Mines and Geology–1966
Compiled by James E. Kahle and Harold B. Goldman

Adopted from U. S. Army, Corps of Engineers, Appendix "E", 1963.
Revisions from: Schlocker, J., 1962; Bonilla, M. G., 1964; Schlocker, J., et al., 1958; Rodbruch, D. H., 1957; Weaver, M. A., and Rodbruch, D. H., 1960; and others.

3000 0 3000 6000
SCALE IN FEET

N



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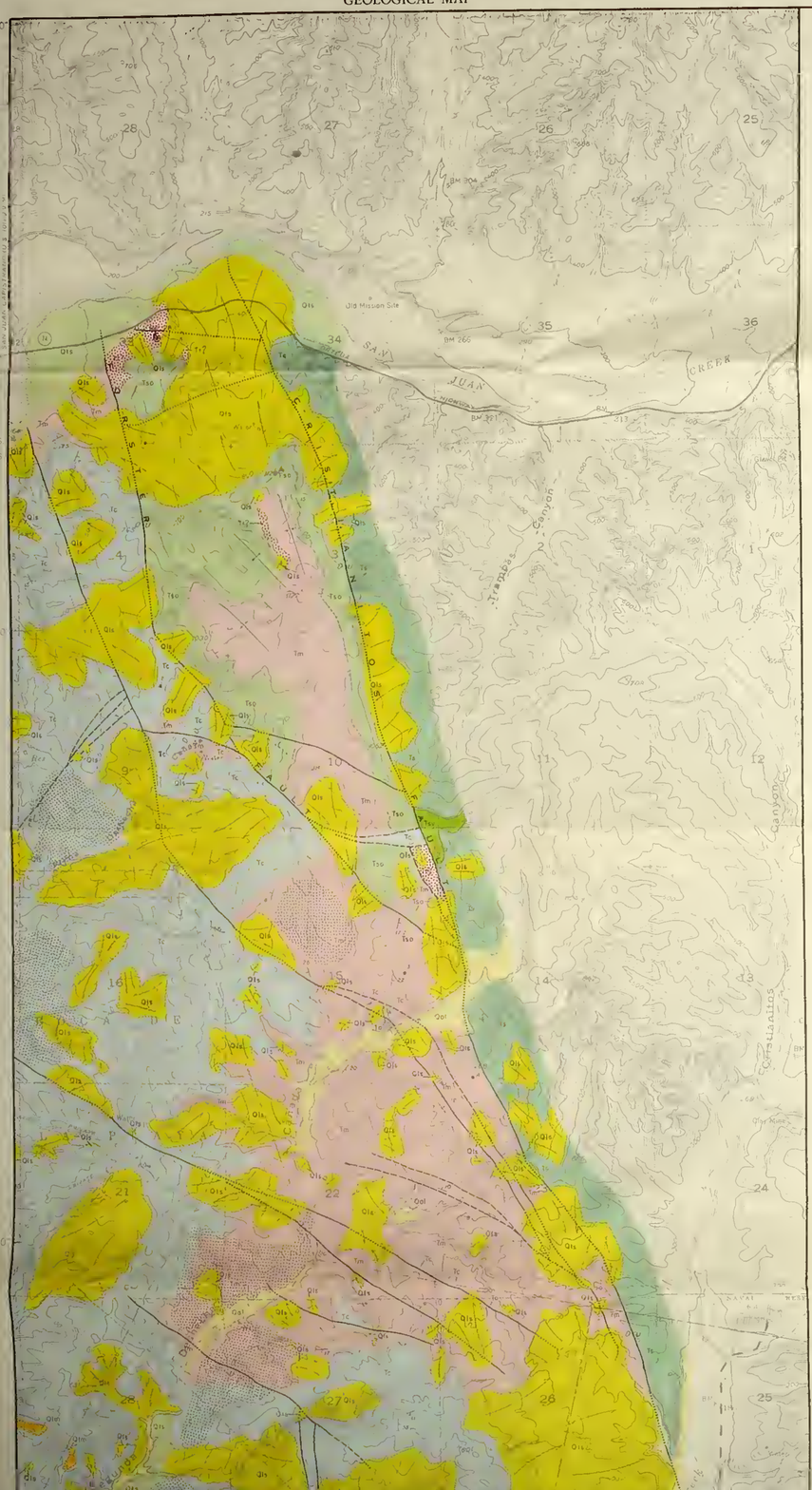
SPECIAL REPORT 98
PLATE 1

GEOLOGICAL MAP


32°30'
Old Mission Site
SAN JUAN CREEK
Trabuco Canyon
Cristianitos Canyon
Cristianitos
Gypsum Canyon
Oso Creek
Arroyo Trabuco
Chiquita Canyon
Rancho Mission Viejo
Ortega Highway
Antonio Parkway
Los Flores Peak
Mount Rose
Tc
Tm
Tso
Ts
Qal
Qls
Qoa
Qsm
Qtm
Qtc
Qtt
Qts
Qoa
Qoal
Qf
Qaf
Qls
Qsm
Qtm
Qtc
Qtt
Qts
Qoa
Qoal
Qf
Qaf
Qls
Tc
Tm
Tso
Ts
Qal
Qls
Qoa

MIDDLE MIOCENE

MIDDLE MIOCENE

UPPER EOCENE? TO LOWER MIOCENE?

EOCENE

Tt

Topanga Formation

Limited distribution in northwestern part of area; light buff to dark brown, massive, calcareous, arkosic sandstone; medium to coarse grained, poorly sorted, moderately to well indurated, with local conglomerate lenses, comprised predominantly of angular feldspar, quartz and biotite, with numerous fragments of glaucophane schist, megafossils common. Forms prominent outcrops, base not exposed, conformably (?) overlain by San Onofre Breccia. Most readily identified by brown color, coarse texture, schist fragments and abundant megafossils. Questionable Topanga Formation shown (Tt?).

Tsv

Sespe and Vaqueros Formations (undifferentiated)

Locally distributed along Cristianitos fault; buff, massive, fine- to coarse-grained, poorly sorted, poorly cemented, arkosic sandstone; locally conglomeratic, lies conformably on Santiago Formation; minor outcrops not mapped. Formations encountered in drill hole below landslide deposits at locality no. 4, 22 feet below surface.

Ts

Santiago Formation

Widely distributed on northeast side of Cristianitos fault; white to gray, massive, fine- to coarse-grained, poorly sorted, unconsolidated, poorly to moderately consolidated, friable, arkosic sandstone; locally comprised of thin interbeds of greenish gray siltstone.

Tm

Monterey Formation

Widely distributed in northeastern part of area; light gray to white, massive, siliceous, fine-grained, hard, brittle, thin-bedded, cherty shale; locally interbedded with light gray, fine-grained, hard, brittle, massive, cherty sandstone; minor outcrops not mapped. Forms prominent outcrops, base not exposed, conformably overlain by Capistrano Formation; outcrops generally limited to occasional exposures in stream bottoms; interfingers with San Onofre Breccia and conformably overlain by Capistrano Formation, very commonly landslid; transitional zone along with Capistrano Formation are most widely landslid rocks in the area; most readily identified by topography, vegetation and black soil. Foraminifers at locality no. 3 indicate lower Mohnian age, at locality no. 4, lower Mohnian age to a depth of 180 feet (questionable Luisian fossils were found near the surface).

Tsb

San Onofre Breccia

Light buff to light gray, massive, coarse, arkosic sandstone and conglomerate; poorly sorted, poorly cemented, friable; comprised of angular fragments of light gray, fine-grained, hard, brittle, thin-bedded, cherty shale, light gray, fine-grained, hard, brittle, massive, cherty sandstone, and fragments of glaucophane schist; locally interbedded with light gray, fine-grained, hard, brittle, massive, cherty sandstone; minor outcrops not mapped. Forms prominent outcrops, base not exposed, conformably (?) overlies Topanga Formation and is both interfingered with and overlain by Monterey Formation, subject to landsliding where slopes are over-steepened and undercut. Most readily identified by dense vegetation, rocky soil and abundance of schist fragments.

SYMBOLS

Contact
Dashed where approximately located, queried where inferred

Fault
Dashed where approximately located, dotted where concealed, U, upthrown side; D, downthrown side

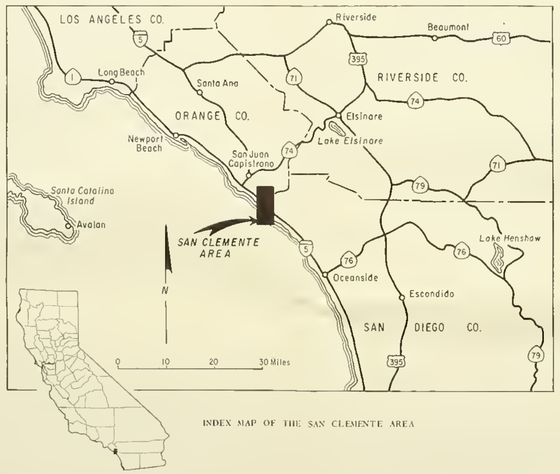
Axis of anticline

Axis of syncline
Dotted where concealed

Strike and dip of beds

Horizontal beds

Fossil localities
Microfossils (Drill hole)
Megafossils



INDEX MAP OF THE SAN CLEMENTE AREA

NOTE

The purpose of this map is to give a broad picture of the slope stability pattern of the area for use in regional planning. It is not meant to be used for any kind of detailed stability analysis of sites to be occupied by specific engineering structures.

This map presents an interpretation of natural slope stability based on the factors of the geology that were apparent by field examination of natural outcrops during 1962–1964. Inherent in the construction of the map is a large degree of generalization of the stability data which leads to a loss in precision for any segment of the map.

This map should be used in conjunction with the stability data in the text of the report.

TOPOGRAPHIC BASE MAP BY U.S. GEOLOGICAL SURVEY

GEOLOGY MAPPED BY R.P. BLANC AND G.B. CLEVELAND 1962-63

GEOLOGICAL AND SLOPE STABILITY MAPS OF THE SAN CLEMENTE AREA, ORANGE AND SAN DIEGO COUNTIES, CALIFORNIA

BY ROBERT P. BLANC AND GEORGE B. CLEVELAND

1 0 1 MILE

CONTOUR INTERVAL 20 FEET

1968

DIVISION OF MINES AND GEOLOGY
IAN CAMPBELL, STATE GEOLOGIST

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF CONSERVATION

DRY MOUNTAIN QUADRANGLE
SPECIAL REPORT 99
PLATE 1

GEOLOGIC MAP AND SECTIONS OF THE DRY MOUNTAIN QUADRANGLE, INYO COUNTY, CALIFORNIA

by B. Clark Burchfiel, 1969

BASE MAP BY U.S. GEOLOGICAL SURVEY

GEOLOGY MAPPED BY BURCHFIEL, 1963-1965

SCALE 1:62500

CONTOUR INTERVAL 80 FEET

DATUM IS MEAN SEA LEVEL

EXPLANATION

- Qal — Alluvium
- Qp — Playa deposits
- Ql — Talus deposits
- Qog — Older alluvium
- Ql — Lake deposits
- Qls — Landslide deposits
- QTb — Basalt
- QTp — Reworked pyroclastic and volcanic rocks
- QTv — Felsic volcanic rocks
- QTl — Older fanglomerate

TERTIARY AND QUATERNARY

- Po — Owens Valley Formation

PENNSYLVANIAN PERMIAN

- PPk — Keeler Canyon Formation

PENNSYLVANIAN

- Mrs — Rest Spring Shale
- Mp — Perdido Formation

MISSISSIPPIAN

- Mtm — Tin Mountain Limestone

UNCONFORMITY

- Dlb — Lost Burro Formation

DEVONIAN

- DShv — Hidden Valley Dolomite

SILURIAN

- Oes — Ely Springs Dolomite
- Oe — Eureka Quartzite
- Oav — Antelope Valley Limestone
- Opu — Pogonip Group undifferentiated

Oav = Antelope Valley Limestone
Opu = Lower Pogonip undifferentiated

ORDOVICIAN

- Cn — Nopah Formation undifferentiated
- Cnd — Dunderberg Shale Member

Cn = Upper Nopah Formation undifferentiated
Cnd = Dunderberg Shale Member

- Cbk — Bonanza King Formation
- Cc — Carrara Formation
- Cz — Zabriskie Quartzite
- Cwc — Wood Canyon Formation

CAMBRIAN

IGNEOUS ROCKS

- Jh — Hunter Mountain Quartz Monzonite
- B — Basic rocks
- S — Silicic rocks

Dikes and sills

SYMBOLS

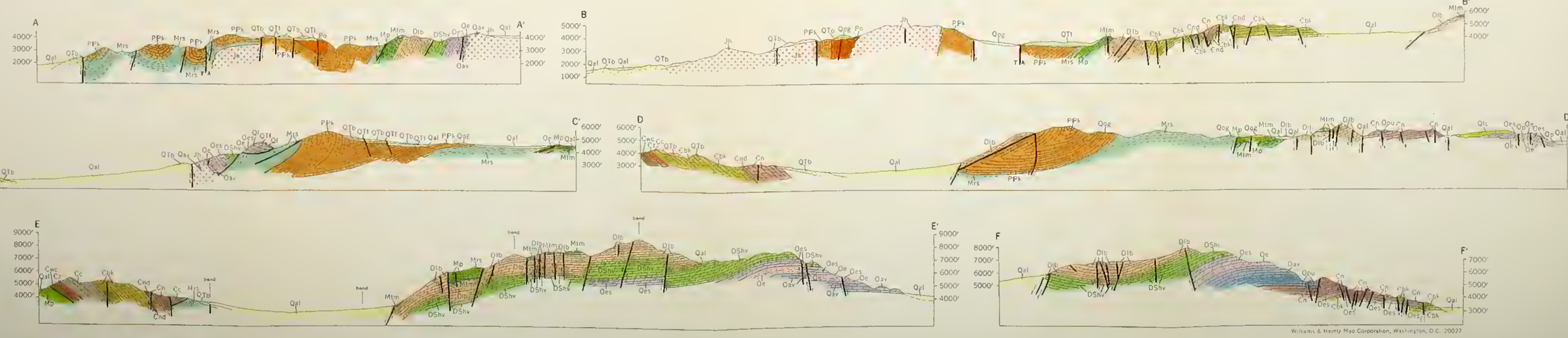
- Contact (*dashed where approximately located*)
- Fault, showing dip (*dashed where approximately located*; U, upthrown side; D, downthrown side)
- Concealed fault
- Fault, showing relative movement
- Thrust fault (*barbs on upper plate; dashed where approximately located, dotted where concealed*)
- Axis of anticline showing direction of plunge
- Axis of syncline showing direction of plunge
- Axis of overturned anticline
- Axis of overturned syncline
- Strike and dip of beds
- Strike and dip of overturned beds
- Strike of vertical beds
- Horizontal beds
- Strike and dip of foliation
- Fault plane in section (A = away, T = toward)

COLUMNAR SECTION OF THE PALEOZOIC ROCKS

PERMIAN	Po	Owens Valley Formation		
PENNSYLVANIAN	PPk	Keeler Canyon Formation		
MISSISSIPPIAN	Mrs	Rest Spring Shale		
	Mp	Perdido Formation		
	Mtm	Tin Mountain Limestone		
DEVONIAN	Dlb	Lost Burro Formation		
SILURIAN	DShv	Hidden Valley Dolomite		
ORDOVICIAN	Oes	Ely Springs Dolomite		
	Oe	Eureka Quartzite		
	Oav	Antelope Valley Limestone	Pogonip Group	
	Opu	Lower Pogonip undifferentiated		
	Cn	Nopah Formation		
	Cnd	Dunderberg Shale Member		
CAMBRIAN	Cbk	Bonanza King Formation		
	Cc	Carrara Formation		
	Cz	Zabriskie Quartzite		
	Cwc	Wood Canyon Formation		

15000′ / 10000′ / 5000′ / 0′

Index Map



Williams & Heintz Map Corporation, Washington, D.C. 20027